The interaction of Solar Radiation Modification with Earth System Tipping Elements

Gideon Futerman[1], Mira Adhikari[2], Alistair Duffey[3], Yuanchao Fan[4], ~~Peter Irvine[3], ~~Jessica Gurevitch[5], Peter Irvine[3], Claudia Wieners[6]

[1]Department of Earth Sciences, University of Oxford, Oxford, OX1 3AN, United Kingdom
[2]Department of Geography, Kings College London, London, WC2B 4BG, United Kingdom
[3]Department of Earth Sciences, University College London, WC1E 6BT, United Kingdom
~~[4]~~[4]Institute of Environment and Ecology, Tsinghua Shenzhen International Graduate School, ~~China~~
~~[5] Department of Ecology and Evolution, Stony Brook~~Tsinghua University, ~~NY 11794-5245~~Shenzhen, 518000, China
[5]Department of Forestry and Natural Resources, Purdue University, West Lafayette, IN 47907, United States of America
~~[6] Institute~~[6]Institute for Marine and Atmospheric Research, Utrecht University, 3584 CC, Netherlands

Correspondence to: Gideon Futerman (GFuterman@hotmail.co.uk)

Abstract. The avoidance of hitting tipping points ~~is often considered a key~~has been invoked as a significant 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.~~Stratospheric Aerosol Injection. 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~~give a first-order indication of the ~~tipping elements, and then assess the available evidence for the~~ impact of SRM on ~~these~~the tipping elements by assessing the impact of SRM on their drivers. 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, when temperature is a key driver of tipping, well-implemented, homogenous, peak-shaving SRM ~~mostly reduces~~is at least partially effective at reducing the risk of hitting most tipping points examined relative to the same emission pathway scenarios without SRM~~, although this conclusion is not clear for every tipping element, and~~. Nonetheless, very large uncertainties remain~~.~~, particularly when drivers less strongly coupled to temperature are important, and considerably more research is needed before many of these large uncertainties can be resolved.

Formatted: Justified

Formatted: Font: 10 pt

Formatted: Justified

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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.~~(Intergovernmental Panel on Climate Change (IPCC), 2023). One aspect of climate change that is gaining increased attention are earth system tipping points ~~(Armstrong McKay *et al*., 2022)~~(Lenton *et al*., 2023), 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).~~(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)~~(Legagneux *et al*., 2018). ~~While climate~~Climate change and biodiversity loss ~~are in themselves~~may influence and reinforce each other (climate-induced habitat loss; reduced CO2 uptake). ,

Solar Radiation Modification (SRM, a.k.a. Solar geoengineering) has been proposed as a set of ~~great concern, their interaction is also of compelling interest, and the potential for~~ methods that could ameliorate some of these climate ~~change~~risks by reflecting a fraction of incoming sunlight and ~~SRM to influence tipping of ecological systems to lower biodiversity systems is also a critical issue. In~~to cool the Earth directly, and is gaining salience at national (National Academies of Sciences and Medicine, 2021) and international (United Nations Environment Programme, 2023) levels. SRM has been discussed 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~~ (Heutel, Moreno-Cruz and Shayegh, 2016; National Academies of Sciences and Medicine, 2021; Bellamy, 2023), but thus far, no comprehensive ~~assessment~~review of the impact of SRM on a variety of earth system tipping elements have been ~~discussed~~performed. 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.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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).~~(Lenton *et al*., 2008; Levermann et al., 2012; 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~~.~~ (e.g., Fig 1a,b). As explicitly stated in ~~Van Nes *et al*., (2016) and Armstrong McKay *et al*. (2022)~~Van Nes *et al*. (2016) and Armstrong McKay *et al*. (2022), and described in nearly all examples in ~~Lenton *et al*. (2008)~~Lenton *et al*. (2008), these qualitative changes are brought about by self-~~accelerating changes~~perpetuating processes caused by ~~a~~ positive ~~feedback~~feedbacks 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.~~ (Fig. 1f).

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~~is threshold-free feedbacks, such as Marine Methane Hydrates ~~(Lenton *et al*., 2008; Van Nes *et al*., 2016; Armstrong McKay *et al*., 2022),~~(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 run-away processes~~.~~ (Fig. 1e). These are commonly discussed alongside tipping elements, so some ~~of these threshold-free feedbacks~~examples will be discussed here. ~~For ease, when~~When referring collectively to the ~~overall set of~~ systems ~~we are dealing with~~discussed in this article, we will use the term 'tipping element' and only ~~clarify that some are in fact feedbacks rather than tipping elements~~classify further 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)~~Not just the magnitude, but also the trajectory of drivers may determine whether tipping occurs. For example, ice sheets have long response times and may only tip if the

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

temperature overshoot is of sufficient duration (Ritchie *et al.*, 2021; Wunderling, Winkelmann, *et al.*, 2022). On the other hand, some tipping elements may be more susceptible to fast changes than to slow changes (rate-induced tipping, fig. 1d), even if the eventual magnitude of the change is the same (Ashwin *et al.*, 2012). Some systems may have more than one driver (e.g., precipitation change and deforestation in the Amazon).

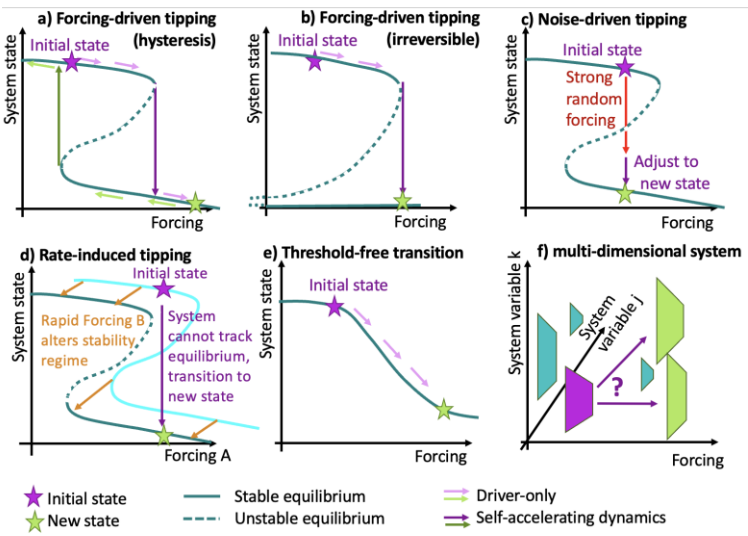


Figure 1 Different tipping processes. Solid (dashed) lines denote stable (unstable) equilibria. a,b) Drivers (change in forcing) push the system closer to the tipping point; when it is reached, the system undergoes self-perpetuating changes ("feedbacks") and reaches a new state. The process can be reversible (possibly with hysteresis) if the forcing is reverted (a) or completely irreversible (b; e.g. loss of a specific ecosystem assemblage due to species extinction). c) Random fluctuations push the system into an alternative state even before the actual tipping point is reached; easier if already close to tipping point. d) Rapid forcing changes prevent the slowly evolving system from tracking its original equilibrium state, causing a transition (rate-dependent tipping). e) Threshold-free feedbacks lead to strong system changes under forcing, but no self-reinforcing dynamics (tipping) occurs. f) Complex systems (e.g.) ecological systems) cannot necessarily be captured by a single system variable and may have many equilibrium states; final outcome may e.g. depend on precise forcing trajectory.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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).~~(Jones *et al.*, 2018). Especially in ecological systems, ~~non-~~drivers not related to climate~~ or CO_2 drivers~~, such as human-induced deforestation, also play a key role~~.~~ (Section 5.2).

~~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~~phasing out (net) greenhouse gas emissions remains the only way to address the root cause of ~~global warming~~climate change, 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~~This includes Solar Radiation Modification (SRM), a ~~suite~~set 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)~~(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~~SAI 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)~~(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

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

their pre-industrial values ~~(Irvine *et al*., 2019)~~(Irvine *et al*., 2019), residual changes to atmospheric, oceanic and ecological systems would remain. SRM might introduce additional effects, such as changes in ~~the~~ regional hydrological cycles relative to both same emission scenario and same temperature scenarios (Ricke *et al*., 2023), or changes in the balance between direct and indirect solar radiation ~~and changes in the ozone layer (United Nations Environment Programme, 2023). SRM and~~ . Alongside its ~~research also have a variety of social and~~physical impacts, the possible political ~~consequences and relevant considerations~~and societal effects of SRM may be equally important, including the risk of conflict ~~(Bas and Mahajan, 2020), securitisation of the climate (Corry, 2017) or~~ (Bas and Mahajan, 2020), mitigation deterrence ~~(McLaren, 2016)),~~(McLaren, 2016), and issues of imperialism ~~(Surprise, 2020)~~(Surprise, 2020), democracy ~~(Stephens *et al*., 2021)~~(Stephens *et al*., 2021) and justice ~~(Horton and Keith, 2016; Táíwò and Talati, 2022)~~(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)~~(MacMartin *et al*., 2022), potentially including a mix of more or less coordinated regional approaches ~~(Ricke, 2023)~~(Ricke, 2023). Unless otherwise specified, we assume a "peak-shaving'' scenario, i.e. 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 1.5ºC above pre-industrial, resembling ~~(MacMartin, Ricke and Keith, 2018; Tilmes *et al*., 2020). Unless specified, we assume all claims of the impact~~MacMartin, Ricke and Keith (2018) and Tilmes *et al*. (2020). Unless specified, we assume the impacts 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~~

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

~~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~~earth 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~~

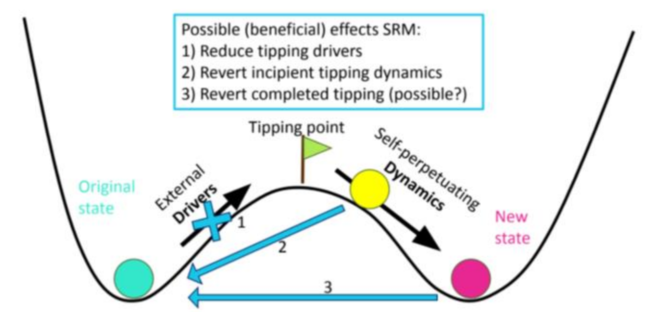


Figure 2. Possible ways by which SRM could counteract tipping.

1) Reducing drivers of tipping before the ~~impacts of SRM on~~ critical threshold (tipping point) is reached. 2) Reverting tipping dynamics (shortly) after it is initialised, but before tipping is completed, such that the tipping feedbacks have begun but the process is not yet complete. 3) Revert tipping after it is completed. This may not be possible or practicable in many cases. While not depicted here, SRM may also adversely affect some tipping points ~~has been conducted~~.

SRM may prevent tipping in several ways (Fig. 2). First, SRM may *prevent* a tipping point from being reached by reducing or counteracting drivers of tipping. This would require a timely implementation of SRM, i.e. before the tipping point is reached. If SRM were terminated before other measures (e.g.

Formatted: Font: Calibri, 11 pt, Italic

Formatted: Font: Calibri, 11 pt, Italic

Formatted: Font: Calibri, 11 pt, Italic

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

negative emissions) are in place to ~~date, though some studies on individual tipping elements exist. Yet while detailed research on potential SRM~~ reduce drivers, SRM may only postpone tipping.

In the absence of direct (modelling) evidence on SRM's impact ~~may be scarce for many~~on a tipping ~~points~~element, a first~~-order~~ indication ~~might~~can be ~~attempted~~obtained by studying how SRM might affect known drivers ~~and dynamics of a given tipping element.~~. If the relevant drivers roughly scale with Global Mean Surface Temperature (GMST~~,~~), we ~~can~~ expect that SRM would reduce the likelihood ~~that this~~of 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~~, particularly due to our much higher uncertainty in modelling studies of the impact of SRM on these climatic variables. Some of these drivers may also strongly depend on the design of the ~~deployment~~SRM scheme.

~~Another difficult question is how~~ SRM ~~interacts with the~~might conceivably revert tipping if tipping dynamics ~~of tipping element once the feedback processes are initiated, and whether it could reverse an ongoing or~~ has already started (process 2 in Fig. 2), but not completed ~~tipping. This is often harder to get first order indicators of, as~~, or even after completion (process 3 in Fig. 2). 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~~, the potential for reversal is often much harder to assess, especially in the absence of dedicated studies. It would be difficult in practice to design SRM for reverting incipient tipping (similar to "emergency ~~solution (Lenton, 2018). However, the lack~~deployment" discussed in Lenton (2018)), because precise prediction of the onset of ~~evidence means~~tipping is impossible (Lenton, 2018). Reversal of completed tipping, even if theoretically possible, might require unfeasibly high SRM intensities in case of hysteresis, and would likely play out over timescales much larger than policy timescales. Therefore we will ~~comment on this question less than the question of preventing or postponing tipping.~~not explicitly discuss it. Our main focus is prevention of tipping drivers, because more evidence is available and because it may be more practically relevant for near-term decision-making. Reversal (process 2 in Fig. 2) will be discussed where appropriate.

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.~~ threshold-free feedbacks, largely following those laid out in Armstrong McKay *et al.* (2022). We aim to provide a preliminary analysis of the

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

interaction of SRM with a wide - but not exhaustive - range of tipping elements. Each section is then structured as follows. Firstly, we assess the drivers and mechanisms of the tipping process. This was done to allow us to then review the impact of SRM on these drivers to give a first order indication of whether SRM could prevent - and to a lesser extent, if it could reverse - tipping. Where available, we also review direct modelling evidence of the effect of SRM on the tipping elements, although many of the models used don't have enough complexity to actually show tipping dynamics in the elements, which is a limitation. Finally, we provide recommendations for future research.

1.4 Results overview

Tipping Element	Effect on Drivers	Reversibility	Strength of evidence base
Greenland Ice Sheet collapse (GIS) (Sect. 2.1)	DC: **Atmospheric warming (+, E)** Precipitation (-, P-O) **Overall: P-E (??)**	**Likely ineffective.** While destabilisation of GrIS could be prevented, reversing previous losses is not possible on multidecadal/centennial timescales due to ice sheet inertia	**Intermediate** - basic theory and several model studies suggest SAI could offset drivers, limited evidence on reversibility
Antarctic Ice Sheet collapse (AIS) (Sect. 2.2)	DC: Atmospheric warming (+, P-E) Ocean warming (+, N-P) Precipitation (-, P-E) CA: Circumpolar deep water driven melt (+, W-N) **Overall: U (???)**	**Likely ineffective.** As ocean thermal forcing is the primary driver of current mass loss, reversal would be difficult on decadal to centennial timescales due to ocean and ice sheet inertia.	**Weak** - the Marine Ice Cliff Instability tipping point is largely theoretical and few studies exist on SAI's impacts on Antarctica.
Mountain Glacier loss (MG) (Sect. 2.3)	DC: Atmospheric warming (+, P-E) Precipitation (-, P-O)	**Likely partially effective.** Atmospheric cooling could reverse the surface elevation feedback,	**Intermediate** - basic theory and several model studies suggest SAI could offset most

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

	Overall: P-E (?)	depending on how much surface elevation has decreased. Cooling may also increase precipitation falling as snow.	drivers, but limited evidence on reversibility and glaciers outside mid latitude Asia.
Winter Arctic sea-ice abrupt loss (WASI) (Sect. 2.5)	DC: **near-surface atmospheric warming** (+, P) **Overall: P (??)**	**Likely effective** with sufficient local cooling.	**Intermediate** – supported by several studies, including inter-modal comparisons, and theory, although no study explicitly assesses the impact of SAI on threshold behaviour.
Summer sea-ice decline, both Arctic and Antarctic (SSI) (Sect. 2.5)	DC: **near-surface atmospheric warming** (+, P-E) CA: Ocean and atm. circulation (+/-,U) **Overall: P-E (?)**	**Likely effective** with sufficient local cooling.	**Intermediate** – supported by several studies, including inter-modal comparisons, and theory
Boreal permafrost thaw (BPF) (Sect. 2.6)	DC: **soil warming** (+, E) Increased precipitation (+, E), CA: increased wildfire (+, U), vegetation change (+/-, U) **Overall: E (??)**	**Likely ineffective** for abrupt thaw. Gradual thaw is likely a threshold-free feedback process without tipping dynamics.	**Intermediate** – supported by several studies, and basic theory for the main driver. However, various processes impacting GHG release from permafrost thaw are not captured in current ESMs.
Marine methane hydrates loss at continental shelf (MMC) (Sect. 2.7)	DC: **ocean warming (at shelf depth)** (+, U) **Overall: U (???)**	**N/A** – methane release from hydrates is likely a threshold-free feedback process without large-scale tipping dynamics. The carbon that had been previously released would	**Weak** – no studies directly assess the impact of SRM.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

		remain in the atmosphere after SRM deployment.	
Atlantic Meridional Overturning Circulation collapse (AMOC) (Sect. 3.1)	DC: **Surface ocean warming** (+,P-E), Precip - Evap increase (+, E-O), CA: **Greenland ice loss** (+,P-E), Sea ice loss (+?, E) **Overall: P-O (??)**	**Uncertain, but possibly partially effective.** Surface cooling might help restart deep convection and deepwater formation. Sea ice expansion may however impede surface heat loss	**Intermediate**. Several modelling studies suggest SRM reduces weakening; models may underestimate AMOC stability.
Sub-Polar Gyre collapse (SPG) (Sect. 3.2)	DC: **Surface ocean warming** (+,P-E), Precip - Evap increase (+, E-O), CA: **Greenland ice loss** (+,P-E), Sea ice loss (+?, E) **Overall: N-E (???)**	**Uncertain, but possibly partially effective.** Surface cooling might help restart deep convection. Sea ice expansion may however impede surface heat loss.	**Weak.** Model disagreement about whether and when SGP could tip. Only one model study dedicated to SRM effect on SGP.
Antarctic Bottom Water collapse (AABW) (Sect. 3.3)	CA: **Antarctic ice melt** (+, N-P). Wind changes, heat flux (?) **Overall: U (???)**	**Unknown.** Dependent on the effect of SRM on Antarctic ice melt.	**Very weak.** Poor process understanding; no dedicated studies on effect of SRM.
Marine Stratocumulus Collapse (MSC) (Sect. 4.1)	DC: GHG forcing (+, N), Atmospheric warming (+, E). **Overall: P (???)**	**Partially effective.** SRM could reverse warming and might reverse tipping point, but not for extremely high GHG forcing.	**Very weak** - This tipping point and SAI's effects on it are largely hypothetical.
Amazon Rainforest Dieback (AR) (Sect. 5.2)	DC: **Drought (+, W-E)**, Atmospheric warming (+, E), Precipitation loss (+, W-E), vapour pressure deficit (+, P-E), CA/NC: **Fire (+, W-P; N for human-caused wildfires)** NC:	**Unknown, but likely ineffective.** Likely heterogenous impacts, and dependent on the very uncertain impacts of SRM on the tipping microclimate.	**Weak**. Weak process understanding, and many relevant processes sub-grid scale so poorly captured in ESMs. It may be highly dependent on deployment scheme.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

	deforestation/degradation (+,N) **Overall: N-P (???)** with regional heterogeneity. In West Amazon, overall W-P (???), however this is less significant for regional tipping than the East Amazon.		
Shallow Sea Tropical Coral Reefs loss (TCR) (Sect. 5.3)	DC: **Surface ocean warming** (+, E), storm intensity (+, P), CA: ocean water acidity (+, W-N), disease spread (+, N-U) NC: Fishing (+, N), Pollution (+, N) **Overall: P-E (?)**	**Likely ineffective to partially effective** with significant regional heterogeneity. After some mass mortality events, corals can reestablish themselves, whereas in other regions macroalgae establish themselves which SRM is unlikely to reverse.	**Intermediate.** Strong process understanding, although the relative importance of drivers still unclear. Very few modelling studies explicitly on the impact of SRM on corals. Some very limited experimental work on MCB.
Himalaya-to-Sunderbans system biodiversity loss (HTS) (Sect. 5.4)	DC: Atmospheric warming (+, P-E), Monsoon precipitation (+/-, U) CA: glacier melt (+, P), sea level rise (+, P) NC: land-use change (+,N) **Overall: P (???)**	Uncertain, likely with significant regional heterogeneity. For example, glaciers could be restored and the ecosystems reliant on them, but in other cases (e.g. where keystone species have gone extinct) reversal may be impossible.	**Weak**. Despite some process understanding, very limited modelling of tipping dynamics or the relative importance of different factors, no explicit studies of the impact of SRM on the system as a whole.
Northern Boreal Forests dieback (NBF) (Sect. 5.5)	DC: **Atmospheric warming (+, E),** permafrost melting (+, E); **Precipitation changes (+/-, P-O);** CA: snow cover loss (+, P-O), wildfires (+, P) CA: Insect outbreak (+,	**Likely effective** over century timescales. Trees that shifted northward could recolonise the tipped areas, although microclimatic effects, and precipitation effects, make this uncertain.	**Weak**. Despite some process understanding and some confidence of SRM's impact on the temperature controlled mechanisms, there is a lack of any modelling of the impacts of SRM

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

	P-E) **Overall: P(??)**		on the forests, which means understanding the impacts of the other factors are very uncertain.

Table 1: The Effect of SRM on Earth System Tipping Elements

Effect on Drivers means the effect of SRM on the drivers of tipping before the tipping point is reached (Stage 1 of Fig. 2). The drivers named here are mostly the "primary drivers" listed in Lenton et al. (2023), although "secondary drivers" have been added when appropriate. We follow Lenton et al. (2023) in referring to Direct Climate (DC) drivers (e.g. warming), Climate-Associated (CA) drivers (eg sea ice loss affecting AMOC), and Non-climate (CA) drivers (e.g. deforestation). We indicate whether the driver impacts tipping by using + (exacerbates tipping) and - (reduces tipping). We then use a letter code to assess the impact of SRM in a scenario with roughly neutralised GMST, as laid out in Section 1.3 on these drivers. ***O****vercompensate (>125%), be nearly* ***E****ffective compensation (75 to 125%),* ***P****artially compensate (25 to 75%),* ***N****ot compensate (-25 to 25%),* ***W****orsen (<-25%) and* ***U****nknown (no judgement can be made). These numbers are necessarily imprecise 'best guesses' based on the evidence. We then use 0-3 question marks to say how large our uncertainty is.*

Reversibility means the effect of SRM on tipping once the tipping point is reached and self-perpetuating feedbacks have set in, but before tipping is complete (Stage 2 of Fig. 2).

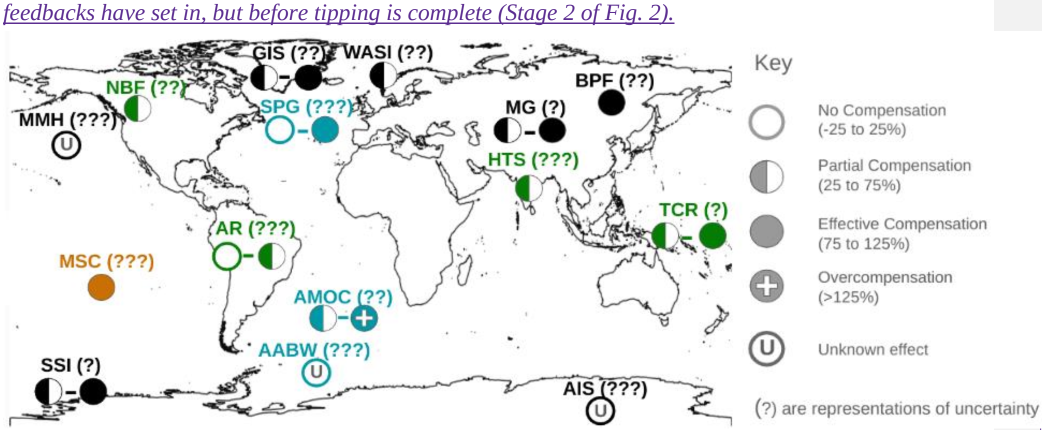


Figure 3: The Effect of SRM on Earth System Tipping Elements

Abbreviations found in Table 1. We colour cryosphere elements black (Sect. 2), ocean elements blue (Sect. 3), atmosphere elements brown (Sect. 4) and biosphere elements green (Sect. 5)

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Out of the 15 tipping elements assessed (Table 1, Fig. 3), the available evidence suggests that SRM would probably reduce tipping drivers at least partially for 10 tipping elements No tipping element was found to have the overall effect of its drivers worsened by SRM, although some tipping drivers were made worse and in some tipping elements (e.g. the Amazon), there may be regions where tipping risk worsens, even if it doesn't overall. For three tipping elements no judgement on the sign of SRM influence could be made due to lack of evidence. Our uncertainty was judged to be considerable to very large for 13 tipping elements. The evidence base was judged as weak or very weak for 8 of the tipping elements, and intermediate for the remaining 7; no tipping element had a strong evidence base for the impact of SRM on it. Compared to SRM's effect on drivers, its potential to reverse ongoing tipping is much harder to assess. If our (highly uncertain) findings are correct, then a well-implemented peak-shaving SRM programme would reduce the probability of tipping for most tipping elements, while using SRM to reverse tipping once it started may be much more difficult and uncertain.

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).~~(Shepherd *et al.*, 2012), its mass balance has become more negative (Otosaka *et al.*, 2023) and surface elevation has also declined (Chen *et al.*, 2021; Yang *et al.*, 2022). 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.~~ (Enderlin *et al.*, 2014; Goelzer *et al.*, 2020). The release of freshwater from melting is also expected to slow the AMOC (Sect. 3.1), affecting global heat transfer (Golledge *et al.*, 2019).

In the future, Greenland appears committed to significant mass loss~~. Aschwanden *et al.* (2019) find that~~, with the ~~Greenland ice sheet could lose between 8-25% of its mass in~~IPCC projecting the ~~next 1000 years even under RCP2.6,~~*likely range* (17-83 percentile range) of sea level contributions of between 0.01-0.1m and ~~up to 100% under RCP8~~0.09-0.18m by 2100 for the SSP1-2.6 and SSP5-8.5~~. The authors~~

Formatted: Font: 14 pt

Formatted: Heading 2, Line spacing: Multiple 1.2 li

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

emissions scenarios, respectively (Fox-Kemper *et al.*, 2021). For 2300, *likely* sea level contributions are more uncertain, but range from 0.11–0.25m for SSP1-2.6 and 0.31–1.74m for SSP5-8.5. Aschwanden et al. (2019) find that the surface-elevation feedback (Sect. 2.1.1) 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~~This study may overestimate 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~~ melt rates, however, due to ~~surface elevation and albedo feedbacks, though the rate~~ the assumption of spatially uniform warming. There is *limited evidence* for complete mass loss from Greenland between 1.5-3°C 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.~~warming, but for 3-5°C, there is *medium confidence* in near-complete loss over several thousand years (Fox-Kemper *et al.*, 2021).

Formatted: Highlight

Formatted: Not Highlight

Formatted: Highlight

2.1.1 Drivers and Feedbacks

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

Surface mass balance describes the balance of accumulation and ~~loss~~ablation 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.~~(Lenaerts *et al.*, 2019). 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)~~(Notz, 2009), allowing more surface melting and a further decrease in elevation ~~(Lenton *et al.*, 2008)~~(Lenton *et al.*, 2008). At a critical threshold, this surface-elevation feedback mechanism could continue unabated. ~~Alongside this, melting~~Melting also exposes bare ice, old ice and ground, and creates melt ponds, all of which have a lower albedo than snow. These

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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).(Notz, 2009). This melt-albedo feedback can be exacerbated by the presence of debris such as black carbon and dust on the ice surface, reducing albedo before melt has even occurred (Goelles, Bøggild and Greve, 2015; Kang *et al.*, 2020). Both of these feedbacks could, however, be partially mitigated by post-glacial rebound. 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. This would counteract some surface lowering, though would likely not occur on useful timescales to alleviate the rapid mass loss if these feedbacks were triggered (Aschwanden et al., 2019).

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)(Irvine, Keith and Moore, 2018). Irvine *et al.* (2009) found that even partially offsetting warming (by decreasing the solar constant) in a 4 x CO2CO_2 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)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) seeApplegate and Keller (2015) find 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)Fettweis *et al.* (2021) also see reduced surface melt through reduction ofwhen reducing the solar constant via G6solarfrom a high forcing to a medium forcing scenario 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)

Using an energy balance model for the whole ice sheet and an ice dynamics model for the Jakobshavn Isbrae drainage basin Moore *et al.* (2019) estimate that Greenland mass loss is decreased by 15-20% under the G4 Geoengineering Model Intercomparison Project (GeoMIP) scenario, which involves a 5 Tg injection of SO_2 per year from 2020 to 2070 under an RCP4.5 scenario, compared with RCP4.5 alone. This is due to the reduction in surface melting and dynamic losses, despite a slight strengthening

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

of the Atlantic Meridional Overturning Circulation increasing heat transfer to high latitudes under G4. Moore *et al.* (2023) then build on this by using two ice sheet models to also include the impact of ocean temperature and dynamic losses for the whole ice sheet. They find that the reduction in ice dynamic losses and surface melt under G4 is strongly model dependent but G4 does reduce both by an average of 35% compared with RCP4.5. Reduction is not uniform due to the topographic differences in drainage basins across the ice sheet.

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~~minimise this shift ~~(Nalam, Bala and Modak, 2018; Smith *et al.*~~(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) .~~(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~~decrease in temperatures and incoming solar radiation is unknown.

2.2 ~~The~~ Antarctic Ice Sheet Collapse

~~The Antarctic ice sheet holds 58m of~~ *Likely* 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 by 2100 range from 0.03-0.27m under SSP1-2.6, to 0.03-0.34m under SSP5-8.5 ~~(Fox-Kemper et al., 2021)~~(Fox-Kemper *et al.* 2021). ~~Furthermore, substantial~~ As for Greenland, there is deep uncertainty in projections to 2300, but these range from –0.14 to 0.78m and –0.27 to 3.14m without the inclusion of marine ice cliff instability (Sect. 2.2.1), for SSP1-2.6 and SSP5-8.5, respectively. Substantial melting would inject large amounts of cold freshwater into the oceans, potentially changing oceanic circulation by inhibiting Antarctic Bottom Water ~~(AABW)~~ formation ~~(Rahmstorf, 2006)~~(Rahmstorf, 2006; Q. Li *et al.*, 2023), a key component in global heat transfer ~~(Bronselaer *et al.*, 2018)~~(Bronselaer *et al.*, 2018). ~~In contrast to the Greenland ice sheet, mass loss from~~ As for Greenland, between 1.5-3°C sustained warming, there is limited evidence on the complete loss of the West Antarctic Ice Sheet, but for 3-5°C, substantial or complete loss is projected for both the West Antarctic Ice Sheet (*medium confidence*) and the Wilkes Subglacial Basin in East Antarctica ~~is~~*(low confidence*) over several thousand years (Fox-Kemper et al., 2021).

Formatted: Font color: Black

Formatted: Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Mass loss from Antarctica is currently driven primarily by the ocean, which melts and thins the base of ice shelves ~~(IMBIE Team, 2020).~~(IMBIE Team, 2020; Fox-Kemper *et al.* 2021). This reduces their buttressing capabilities, ~~increasing~~which can increase ice velocities and discharge into the ocean ~~(Alley *et al.*, 2015).~~(Gudmundsson *et al.*, 2019). Current Antarctic air temperatures mean surface melting is limited and not a major component of direct mass loss, but ~~this could change~~it is expected to increase the likelihood of ice shelf disintegration in future ~~with rising atmospheric temperatures (DeConto and Pollard, 2016).~~(van Wessem *et al.*, 2023).

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~~due to ice sheet ~~instability (MISI) and marine ice cliff instability (MICI).~~

instabilities. The West Antarctic Ice Sheet is grounded almost completely below sea level ~~and many~~(Morlighem *et al.*, 2019). Many areas are situated on reverse (retrograde) 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~~and so it slopes ~~down~~downwards inland (Weertman, 1974).

Formatted: Font color: Black

Formatted: Font color: Black

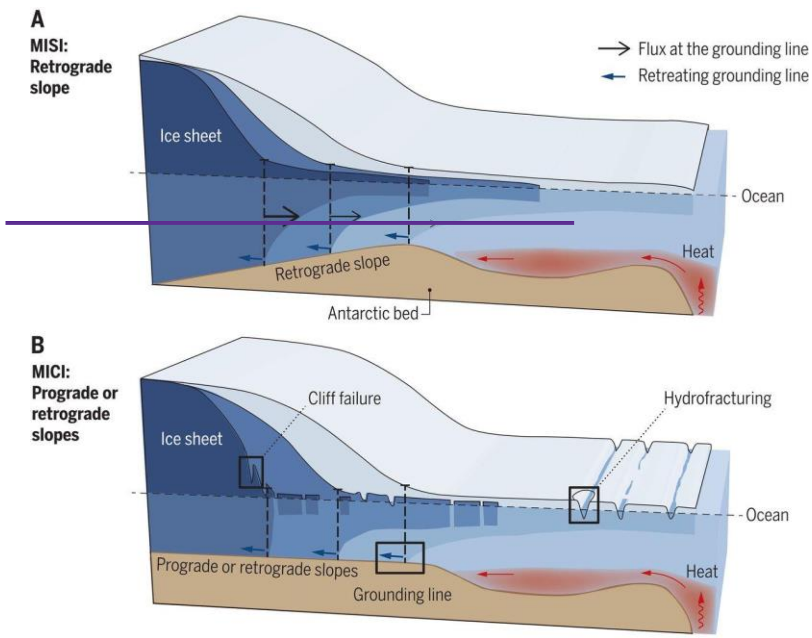
Formatted: Font: Calibri, 11 pt

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)



~~*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 marine ice sheet instability (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~~(Pattyn, 2018). If grounding line retreat reaches the reverse slope of the bed, a tipping point can be initiated as continued retreat puts the grounding line in 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)).~~(Weertman, 1974; Gudmundsson, 2013).

Formatted: Font: Calibri, 11 pt

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Parts of the East Antarctic Ice Sheet are similarly grounded below sea level with reverse bed slopes and so are also potentially 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.* (Rignot *et al.*, 2019).

The major driver of MISI is ocean thermal forcing, responsible for meltinge.g. from the base of the ice shelves (Gudmundsson, 2013). In Antarctica, MISI is also influenced by upwelling of warmer circumpolar deepCircumpolar Deep Water. This water (CDW), whichmass can be more than 4°C warmer than the freezing point and is widely believed to be a current driver of driving basal melting in the Amundsen sea (Jacobs *et al.*, 2011).Sea Embayment (Jacobs *et al.*, 2011). CDW upwelling is wind driven, and may have been influenced by anthropogenic climate change, 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). (Dotto *et al.*, 2019; Holland *et al.*, 2019).

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).

MISI is thought to be a key driver of possible collapse above 2°C and 3°C atmospheric warming for the West and East Antarctic ice sheets, respectively (Golledge *et al.*, 2015; Pattyn, 2018; Garbe *et al.*, 2020; Lipscomb *et al.*, 2021). The IPCC (Fox-Kemper et al., 2021) states that “the observed evolution of the ASE glaciers is compatible with, but not unequivocally indicating an ongoing MISI” ((Fox-Kemper et al., 2021), Fox-Kemper *et al.*, 2021).

Formatted: Font color: Black

Formatted: Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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)~~(Bassis and Walker, 2011). Therefore, ~~it is speculated that,~~ if ice shelf disintegration produces cliffs of this height, it may potentially trigger a self-sustained collapse and retreat of the grounding line ~~could be triggered (Pollard, DeConto and Alley, 2015)~~(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 the duration of this self-sustained collapse is uncertain, though (Pollard, DeConto and Alley, 2015) see the West Antarctic Ice Sheet collapse in decades.~~ (Wise *et al.*, 2017), and is a highly uncertain process (Edwards *et al.*, 2019). Rates and duration of this self-sustained collapse are poorly known. The IPCC (Fox-Kemper et al., 2021) states that there is *low confidence* in simulating MICI. Models that invoke MICI processes present higher sea level rise projections than most other studies (DeConto *et al.*, 2021). Under 2°C warming, (DeConto *et al.*, 2021) project the rate of mass loss to 2100 as similar to present day, but at 3°C, this jumps by an order of magnitude, increasing further for more fossil fuel intensive scenarios.

MICI's drivers are similar to MISI, as both ~~involve~~ can be preceded by ice shelf disintegration ~~and so are vulnerable to~~from ocean thermal forcing~~ and circulation melting the base of the ice shelf (Pritchard *et al.*, 2012).~~. Atmospheric temperatures ~~are~~can 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~~ influence ice shelf 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.~~

Formatted: Font: Not Bold

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

~~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.~~ through hydrofracture (Trusel *et al.*, 2015; van Wessem *et al.*, 2023).

2.2.2 The impacts of SRM

There are ~~virtually no~~few studies which focus on ~~SRM's~~the impact of SRM on the East or West Antarctic Ice Sheet, but there is evidence to suggest that ~~SRM~~it would cool ~~the Antarctic (Visioni *et al.*, 2021)~~surface air temperatures around Antarctica (Visioni *et al.*, 2021), which ~~would be useful in limiting ice sheet deterioration via~~may limit hydrofracturing. ~~SRM may~~SRM may be more limited in its ability to prevent Antarctic tipping points, however, as the ocean takes decades to centuries to respond to a change in atmospheric forcing. This is seen by Sutter *et al.* (2023) who find that committed Southern Ocean warming means that under RCP4.5, SRM would have to be deployed by mid century to delay or prevent a West Antarctic Ice Sheet collapse. Under RCP8.5, however, SRM cannot prevent collapse. Hysteresis experiments find that regrowth occurs much more slowly than mass loss (Garbe et al., 2020). DeConto *et al.* (2021) show that the ocean's slow response to atmospheric thermal changes means that while implementing Carbon Dioxide Removal (CDR, which may have a somewhat similar thermal effect to SRM) in the first half of this century could reduce sea level rise compared to a 3°C warming scenario it cannot reverse it. SRM may also 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, 2012).

~~McCusker, Battisti and Bitz (2015)~~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).~~(Keith *et al.*, 2016). In addition, the poleward shift seen from ~~McCusker, Battisti and Bitz (2015)~~ tropical injection location (McCusker, Battisti and Bitz, 2015) is not seen for a southern hemisphere injection where the jet shifts equatorward ~~(Bednarz *et al.*, 2022; Goddard *et al.*, 2023). Goddard *et al.* (2023)~~(Bednarz *et al.*, 2022; Goddard *et al.*, 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~~5°C above preindustrial could prevent possible collapse of much of the Antarctic ice sheet.

Formatted: Font: 12 pt

Formatted: Line spacing: single

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

~~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~~In summary, SRM would therefore likely be effective in reducing surface melting and hydrofracturing, but it would not be as effective at reducing basal melt. 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).~~(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 to Antarctica than doing nothing at all~~, as~~: in a warmer, non-SRM world, ~~the resulting increase in~~increasing precipitation may slightly offset some mass loss ~~(Edwards *et al.*, 2021; Stokes *et al.*~~(Edwards *et al.*, 2021; Stokes *et al.*, 2022).

2.3 Mountain ~~Glaciers~~Glacier Loss

Current trends of glacier mass balance globally are negative ~~(Fox-Kemper et al, 2021),~~, with glacier mass loss accounting for ~~~20-30~~40% of current observed sea level rise ~~(Zemp *et al.*, 2019; Rounce *et al.*, 2023)~~from 1901-2018 (Zemp *et al.*, 2019; Rounce *et al.*, 2023). ~~Zemp *et al.* (2019)~~Zemp *et al.*,

Formatted: Font color: Black

Formatted: Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

(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).~~(Marzeion *et al.*, 2018, 2020; Zekollari, Huss and Farinotti, 2019). Sustained warming of 1.5-3°C is projected to result in glacier mass loss of 40-60%, increasing up to 75% for 3-5°C (*low confidence*, Fox-Kemper e*t al.*, 2021).

2.3.1 Drivers and Feedbacks

Mountain glaciers are, like Greenland, subject to the surface-elevation and melt-albedo feedbacks ~~(Johnson and Rupper, 2020),~~ which ~~would not only raise sea levels,~~ could lead to unabated retreat (Johnson and Rupper, 2020), but due to their smaller size, they are more sensitive to climatic changes and respond on shorter timescales. They are also ~~reduce~~affected by additional local drivers and feedbacks such as changing snow patterns and slope instabilities. These local feedbacks are not discussed here as we are focused on the ~~availability of fresh water for~~global scale processes affecting mountain ~~communities. Rounce *et al.* (2023)~~glaciers more generally.

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~~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)~~(Irvine, Keith and Moore, 2018). ~~Zhao *et al.* (2017)~~Zhao *et al.* (2017) find that ~~although~~though SRM can limit mass loss from all glaciers in high mountain Asia by 2069, retreat ~~by 2069~~is still observed 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.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

~~As~~ G3 involves a gradual increase in the amount of SO_2 injected to keep global average temperature nearly constant under an RCP4.5 scenario (Kravitz *et al.*, 2011).

SRM is more effective at counteracting hydrological changes than temperature changes ~~(Ricke *et al.*, 2023),~~(Ricke *et al.*, 2023), so while melt may be reduced, surface mass balance could be ~~negatively affected by~~decreased overall through reduced snowfall in the accumulation zone. Idealised experiments using a reduction of the solar constant to halve the warming resulting from doubled ~~CO2~~CO_2 indicate that negligible amounts of the planet would see substantially reduced precipitation compared to preindustrial ~~(Irvine *et al.*, 2019)~~(Irvine *et al.*, 2019), but precipitation changes from SRM specifically are unlikely to be uniform. ~~(Zhao *et al.*, 2017)~~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. Outside of the Himalayan region, there is a lack of research on precipitation impacts.

2.4 Land Ice Further Research

Currently, there are large gaps in the literature and high model uncertainty 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~~There is a need for multi-model ensembles forced by various SRM scenarios, ~~to include~~including aerosols other than sulphate and methods other than SAI. As suggested in Irvine~~ et al.~~, Keith and Moore (2018), the inclusion of ~~Geo-MIP~~GeoMIP scenarios in the Ice Sheet ~~(Nowicki *et al.*, 2016)~~(Nowicki *et al.*, 2016) and Glacier ~~(Hock *et al.*, 2019)~~(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~~allow direct comparisons with standard emission 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 SAI 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)~~Bednarz *et al.* (2022) find that a northern hemisphere SAI injection with sulphate drives a positive ~~SAM~~southern annular mode, whereas southern hemisphere injection results in a negative

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

~~SAM~~southern annular mode 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)~~(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)~~(Lee *et al.*, 2021): expanding this to land ice would also 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)~~(Fetterer, 2017).

~~Late summer~~ The annual Arctic sea~~-~~-ice minimum extent has declined by 50% since satellite observations began in the late 1970s ~~(Fetterer, 2017).~~(Fetterer, 2017). The Arctic is expected to be seasonally ice-free by mid-century; a majority of CMIP6 models ~~see~~have ice-free periods during the Arctic summer by 2050 under all plausible emissions scenarios ~~(Notz and SIMIP Community, 2020).~~(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)~~(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).~~(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~~was at the lowest extent on record in 2022, only to be surpassed ~~with~~by a new record low in February 2023 ~~(Fetterer, 2017)~~(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~~.~~ (Roach *et al.*, 2020).

2.5.1 Drivers and Feedbacks

On decadal time-scales, ~~temperature is the main control on~~ Arctic sea~~-~~-ice ~~(Notz and Stroeve, 2018)~~area has declined linearly with the increase in global mean temperature over the satellite period in all months (Notz and Stroeve, 2018). Local radiative balance at the sea-ice edge may also be an important control

Formatted: Font: Italic

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

on Arctic sea ice extent ~~(Notz and Stroeve, 2016)~~(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%)~~(Stroeve *et al*., 2011; Mallett *et al*., 2021). Unlike in the Arctic, almost all 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)~~(Masson-Delmotte *et al*., 2021).

Sea ice under global warming is subject to the ice albedo feedback ~~(Serreze *et al*., 2009)~~(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).~~(North, 1984; Merryfield *et al.* 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)~~(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)~~(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 the large scale climate forcing within 1-2 years of complete removal ~~(Tietsche *et al*., 2011)~~(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)~~(Notz and Stroeve, 2018). Both satellite observations (Notz. and Marotzke. no date; 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~~perpetuating, 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).~~(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).~~(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)~~(Bathiany *et al*., 2016). Local positive

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

feedback processes may also contribute to the abrupt winter Arctic sea-ice loss seen in some models (Hankel and Tziperman, 2021).

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).~~(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.~~(Jones *et al.* 2018; Jiang *et al.*, 2019; Lee *et al.*, 2020, 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).~~(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.*~~(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).~~(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)~~(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).~~(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)~~2015; (Lee *et al.*, 2021, 2023), potentially more efficiently per unit SO_2 injection than low latitude injection strategies ~~(Lee *et al.*~~(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).~~(Berdahl *et al.*, 2014; Jiang *et al.*, 2019; Lee *et al.*, 2021, 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).~~(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).~~(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

Formatted: Font color: Black
Formatted: Font color: Black
Field Code Changed
Formatted: Font color: Black
Formatted: Font color: Black
Field Code Changed
Formatted: Font: 10 pt
Formatted: Font: 10 pt
Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

winter near-surface air temperatures ~~(Berdahl *et al.*, 2014; Jiang *et al.*, 2019; Lee *et al.*, 2021; Lee *et al.*, 2023).~~relative to the same emissions pathway without SRM (Berdahl *et al.*, 2014; Jiang *et al.*, 2019; Lee *et al.*, 2021, 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).~~(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~~(Tilmes *et al.*, 2018; Jiang *et al.*, 2019). 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 relative to the target world, 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)~~(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)~~(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~~ Ridley and Blockley (2018) is a notable exception - assessing the ~~study~~different impact of ~~(Ridley and Blockley, 2018), quantifying the change in~~ SRM versus avoided emissions on Arctic and Antarctic climate and sea ice under SRM~~ with comparison to the expected change~~, at ~~the level of~~a given global ~~warming under that SRM scenario. As such, further research is required to quantify~~mean temperature. Such assessments would aid in making a fully quantitative statement on the effectiveness of ~~different~~ SRM strategies for ~~Arctic~~sea-ice restoration ~~(Duffey *et al.*~~(Duffey *et al.*, 2023).

Formatted: Font color: Black

Formatted: Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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).~~(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).~~(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).~~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)~~(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 deep thaw occurring on rapid timescales of days to several years due to processes such as the physical collapse of the surface caused by ice melt ~~(Turetsky et al., 2020).~~and the formation of thermokarst lakes (Schuur *et al.*, 2015; Turetsky *et al.*, 2020). Such abrupt thaw may increase the strength of the permafrost carbon feedback substantially relative to that modelled in ESMs~~.~~, which do not include these processes. 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,~~

Formatted: Font: Italic

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

2020).(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).(Slater and Lawrence, 2013). Various other factors also impact soil temperature however, including vegetation cover, precipitation type and amount, and wildfire (Grosse et al., 2011).(Grosse *et al.*, 2011). For example, summer rainfall fluxes sensible heat into the soil, increasing thaw (Douglas, Turetsky and Koven, 2020),(Douglas, Turetsky and Koven, 2020), and snow cover over winter insulates the soil, increasing its annual mean temperature (Zhang, Osterkamp and Stamnes, 1997).(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^{o}C of local warming for near-synchronous and rapid thaw of large areas of permafrost, particularly Yedoma deposits (Strauss et al., 2017),(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).(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. This potential global tipping point is in addition to the widespread occurrence of localised abrupt thaw which could occur at warming above approximately 1.5°C (Armstrong McKay *et al.*, 2022).

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).(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)(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)(Jiang *et al.*, 2019; Lee *et al.*, 2019, 2023; Chen, Liu and Moore, 2020; Chen *et al.*, 2023; Liu, Moore and Chen, 2023).

Formatted: Font: Italic

Formatted: Font: Italic

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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)~~(Chen, Liu and Moore, 2020), so ~~the single~~ multi-model assessments ~~need to be treated with caution~~are desirable. 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).~~(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).~~(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).~~(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.*~~(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~~reverse tipping ~~in~~once 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. Similarly, while SRM might reduce the onset of localised abrupt thaw processes, it would be unlikely to reverse these processes once begun.

Emissions from thawed permafrost are irreversible on centennial timescales ~~(Schaefer *et al.*, 2014; Schuur *et al.*, 2022).~~(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.

Formatted: Font color: Black

Formatted: Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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.~~ The permafrost response in ESMs does not include the feedback processes leading to abrupt thaw and local tipping behaviour (Turetsky et al., 2020), so the quantitative assessments above principally apply to the gradual thaw component; further development of ESMs to include such processes would allow more robust quantitative assessment of the impact of SRM (Lee *et al.*, 2023). ~~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).~~.

Greater understanding is also 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.

2.7 Marine Methane Hydrates Release

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).

Formatted: Heading 1, Line spacing: single

Formatted: Font: 10 pt

Formatted: Font: 10 pt

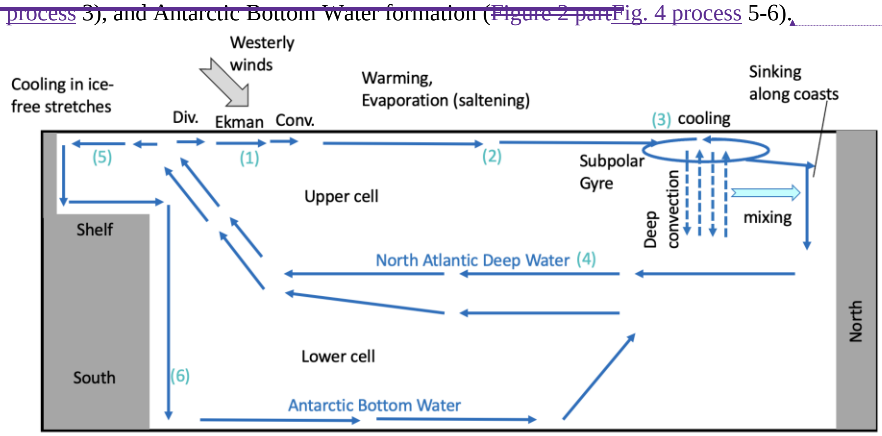
Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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~~the multi-centennial timescale of deep-ocean heat uptake, 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),~~(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).~~(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~~Fig. 4): The Atlantic Meridional Overturning Circulation (AMOC; ~~Figure 2 part~~Fig. 4 process 1-4), deep convection in the north Atlantic Subpolar Gyre (~~Figure 2 part~~SPG, Fig. 4 process 3), and Antarctic Bottom Water formation (~~Figure 2 part~~Fig. 4 process 5-6).



Formatted: Font: Calibri

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

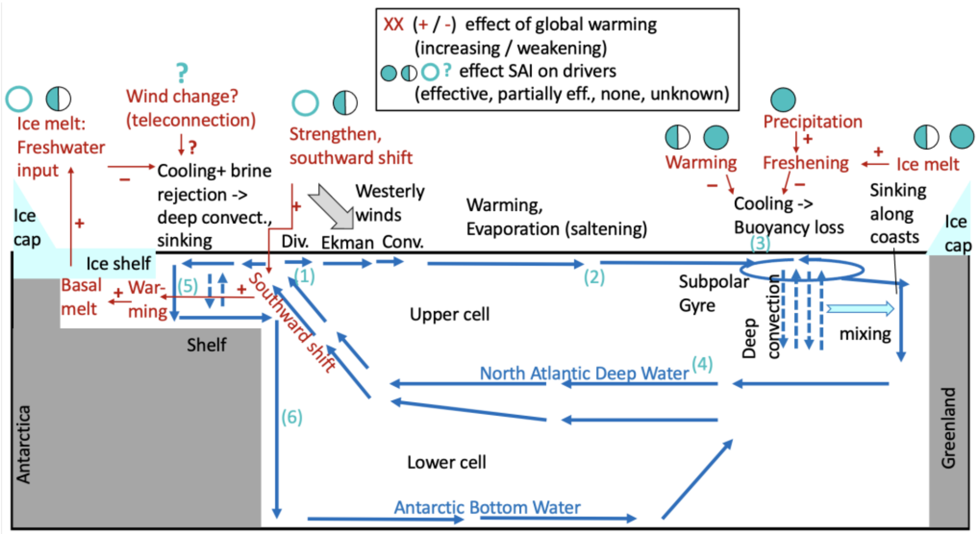


Figure ~~2.~~4: Schematic of the Atlantic circulation. (1) Westerly winds around 40ºS drive a northward Ekman transport, ~~causing~~south of which divergence ~~to the South and enabling~~enables the upwelling of North Atlantic Deep water. (2) To the north, water moves northwards, warming and saltening ~~(~~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 (AABW) is formed in sea-ice-free stretches around Antarctica, where water is exposed to cold air~~. (6)~~ and salinification through brine rejection. It sinks along the shelf edge and feeds the lower circulation cell. Global warming may warm and freshen surface water in the North Atlantic, reducing deep convection and weakening the Atlantic Meridional Overturning Circulation and the Subpolar Gyre (3); SRM is likely partially effective to effective. In the South, global warming can affect Antarctic meltwater input by increasing the upwelling of warm water onto the shelf, hindering densification and hence Antarctic Bottom Water formation (5). SRM is likely not fully effective (Section 3.3). The effect of other drivers, e.g. wind change, on AABW formation is uncertain.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

3.1 Atlantic Meridional Overturning Circulation (AMOC) Collapse

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.~~(fig. 5). In order to sink, this water must be sufficiently dense compared with the deeper water~~. If the~~, therefore surface ~~water in the North Atlantic becomes warmer~~warming or ~~fresher, this~~freshening 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) .~~(Marshall and Speer, 2012), (Johnson *et al.*, 2019).

~~AMOC generally weakens in coupled climate~~Climate models project AMOC to weaken under ~~climate change. (Weijer *et al.*, 2020)) find that AMOC declines:~~global warming, but in general do not predict collapse until 2100 (Weijer 2020), although some do for ~~newer~~extreme hosing (Jackson 2023, van Westen 2023) or warming (Hu et al., 2013). Climate models ~~(CMIP6) by 24% between present-day~~might underestimate AMOC stability, 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 can 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~~ (collapse) 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~~ present conditions is still an open debate (see SI). Note that 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.~~

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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 lasting for decades or more (fig. 4 of Loriani *et al.*, (2023)), even without actual tipping (fig. 3d)..

3.1.1 Drivers and Feedbacks

Global

In the North Atlantic, global warming could reduce North Atlantic surface water density (and hence weaken and potentially tip AMOC) through heat flux or freshwater flux, i.e. changessurface warming and freshening. Freshening could stem from an increase in precipitation minus evaporation, sea ice melt, 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)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)However, 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)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).); they find that sea ice retreat eventually weakens AMOC. Using an intermediate complexity model, Golledge *et al.* (2019)Golledge *et al.* (2019) found that future freshwater fluxes from Greenland (and Antarctica) derived from ice sheet models under RCP8.5 forcing might weaken AMOC by 3-4Sv. If AMOC can indeed tip, then icemelt would likely increase the

Formatted: Pattern: Clear (Custom Color(RGB(178,254,253)))

Formatted: Font: 10 pt

Formatted: Font: 10 pt

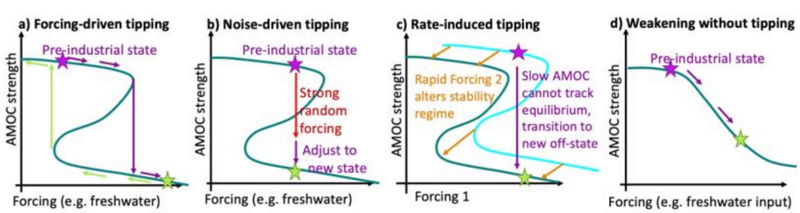
Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

probability. Atmospheric circulation changes, e.g. North Atlantic Oscillation (NAO), may also affect AMOC, for example by introducing heat flux anomalies ~~(Delworth 2016).~~(Delworth and Zeng, 2016).

In the Southern Ocean, climate change might influence the position or strength of the westerly winds potentially affecting AMOC's upwelling branch. However, changes in eddy fluxes might (partly) compensate the change in westerlies (Marshall and Speer, 2012).

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~~Whilst the classic view is that a gradual change in forcing would eventually tip AMOC (~~fig. 3a~~Figure 1a), 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)).~~Figure 1c, 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 1d, 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~~

Formatted: Font: 15 pt

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

~~MCB~~SRM is likely to reduce most drivers of AMOC weakening. Using GeoMIP (Kravitz *et al.*, 2011) data, Xie et al., (2022) found that in the highly idealised G1 experiment, where the GMST effect of instantaneous quadrupling of CO2 is compensated by instantaneous solar dimming, the GHG effect on heat flux in North Atlantic deep convection regions is Partially to Effectively compensated (3 models), while the effect on precipitation minus evaporation is Effectively compensated to Overcompensated (6 models) and September sea ice loss is Effectively compensated (6 models). SRM is expected to Partially to Effectively prevent Greenland tipping (Sect. 2.1), which suggests it may reduce freshwater input from ice melt.

Several studies directly modelled the effect of SRM (or analogues) on AMOC weakening without separating the effect on various drivers. Hassan *et al.* (2021) showed that anthropogenic aerosols, in absence of Greenhouse forcing, increased AMOC by about 1.5Sv in the 1990s, with surface heat flux dominating over freshwater flux. Xie *et al.* (2022) used simulations of various SRM methods, including SAI, solar dimming, increasing ocean albedo (a rough proxy for Marine Cloud Brightening (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~~,~~ (experiment G1), AMOC strength is ~~not fully but nearly~~Effectively restored in the multi-model mean, with solar dimming performing slightly better and MCB slightly worse than SAI. Note that in G1 there is no period of global warming, as solar dimming starts simultaneously with CO2 increase, while in reality, AMOC changes may be locked in before SRM starts. Using the CESM2-WACCM model, ~~(Tilmes *et al.*, 2020)~~Tilmes *et al.* (2020) found that if SRM is used to cool RCP8.5 forcing back to 1.5 degrees from 2020, 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).~~(Fasullo *et al.*, 2018; Tilmes *et al.*, 2018). This suggests that SRM's overall effect on AMOC weakening is partial compensation to overcompensation. Given the similarity in drivers for AMOC weakening and tipping, we assess the effect of SRM on AMOC tipping to be partial to overcompensation, too.

~~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.~~

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

The ~~presence of~~ potential rate~~-~~-dependency of ~~the AMOC tipping (Lohmann and Ditlevsen, 2021)~~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~~so the possible effects of SRM on this mechanism remain uncertain too.

~~If AMOC is prone to rate-dependent~~ As for noise-induced 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 sudden termination of SRM could lead to higher rates of change and increase tipping risks. It~~ 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~~. However, SRM may ~~influence how close~~help to keep AMOC ~~is to~~further from the tipping point, which ~~also~~would reduce 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~~An extension of sea ice cover after AMOC tipping (or weakening) may shield the ocean from surface cooling (van Westen and Dijkstra, 2023), rendering SRM less effective or potentially counterproductive. Even if SRM can restore AMOC, very strong SRM might be required if AMOC shows hysteresis, and this forcing may have to be applied for many decades, with potentially detrimental consequences. ~~(Schwinger *et al.*, 2022)~~Schwinger *et al.* (2022) demonstrate this by simulating the effect of instantaneous ~~Carbon Dioxide Removal~~CDR, and hence instant cooling, on a ~~a~~ weakened (i.e. not even ~~tippied~~tipped) 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~~ Pflüger *et al.* (2024) simulate an abrupt SAI onset in 2080 and find ~~North Atlantic overcooling due to prolonged~~ that AMOC weakening ~~under a delayed SRM scenario.~~ is halted, but not reverted, by 2100, leading to prolonged overcooling in the North Atlantic. Attempts to restore a tipping or fully tipped AMOC might lead to even more severe and extended overcooling. Conversely, potential attempts to minimise overcooling by slowly ramping up SRM may conflict with requirements for preventing other tipping points.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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~~can not tip, ~~a significant prolonged weakening may already have severe consequences, making~~ SRM's impact on AMOC weakening ~~a worthy~~remains an important research subject~~ even in absence of tipping~~.

3.2 North Atlantic Sub-Polar Gyre Collapse

~~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 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.~~
There are indications that deep convection in the subpolar gyre (SPG) in the North Atlantic may collapse without full AMOC collapse, although it is uncertain whether the SPG is a tipping element (see SI).

3.2.1 Drivers and Feedbacks

~~The studies, leaning on Born and Stocker (2014), suggest the following mechanism for SPG collapse.~~As is the case for AMOC, the main drivers are surface warming and processes leading to surface freshening. Sgubin *et al.* (2017) and Swingedouw *et al.* (2021) leaning on Born and Stocker (2014),

Formatted: Line spacing: Multiple 1.2 li

Formatted: Pattern: Clear (Custom Color(RGB(230,202,254)))

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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.

3.2.2: The impact of SRM

SRM's effect on the drivers are similar to the discussion in Sect. 3.1, although the relative importance of these drivers may differ.

Direct simulations of SRM's effect on the SPG are extremely scarce, with Pflüger *et al.* (2024) being the only study at date - to the authors knowledge - to analyse the impact of SRM on SPG tipping. They~~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.~~

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

To our knowledge, no study has explicitly simulated SPG recovery due to SRM. Plüger *et al*~~.,~~. (2024) find that, when cooling an RCP8.5 scenario down to 1.5ºC from 2080 using SAI, ~~find that~~ SPG convection remains in the collapsed state ~~except~~at least for ~~one year, but that surface density continues to increase, suggesting a possible recovery after 2100~~several decades.

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~~Some possible research avenues overlap with AMOC (sect 3.1.3), including improving process understanding in the North Atlantic and quantifying SRM's impact on drivers there. As opposed to AMOC weakening (Xie *et al.*, 2022), to our knowledge SPG changes have not been systematically reviewed in GeoMIP data. As some climate models actually 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 Overturning Circulation and Bottom Water formation

~~-~~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~~).~~) and brine rejection during sea ice formation. It sinks to great depth, filling the abyssal ocean and constituting the lower branch of the lower Atlantic circulation cell~~.~~ (Fig. 2, ~~(~~process 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~~

Formatted: Font: Italic

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

the 21st century as a result of Antarctic ice sheet melt, but does not predict a tipping point or complete shut-down.

Process understanding is still limited, as most climate models do not resolve small-scale processes such as circulation in ice shelf cavities, and meltwater input from Antarctica is typically not included (Fox-Kemper *et al.*, 2021). Observational and modelling evidence suggest a future weakening of AABW formation, and AABW formation collapse has been listed as a potential tipping point (Armstrong McKay *et al.*, 2022; Loriani *et al.*, 2023; see also SI).

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.

A modelling study by Q. Li *et al.* (2023) finds that the major driver of AABW formation decline is meltwater input from Antarctica, which freshens the surface water flowing towards Antarctica (point (5) in Figure 5) and inhibits sinking. In contrast, another modelling study (Zhou *et al.*, 2023) finds that AABW formation in the Weddell sea has declined due to a decrease in southerly winds near the ice shelf edge, which push sea ice away from the shelf edge, thereby enabling surface cooling in the open water and sea ice production and hence brine rejection, both of which help increase density. The study suggests that the local wind changes are at least partly driven by natural variability over the Pacific, transferred through teleconnections. In addition, global warming is predicted to cause an intensification and southward shift of the westerlies around Antarctica (Goyal *et al.*, 2021), leading to intensified upwelling of warm water around Antarctica. Dias *et al.* (2021) suggest that this may reduce sea ice cover and enhance surface cooling, convection and ultimately AABW formation, although this may be overestimated in models with overly large stretches of open ocean. Note that ocean warming around

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Antarctica is also expected to accelerate ice loss (Sect. 2.2) and hence freshwater input, which would again reduce AABW production (Q. Li et *al.*, 2023).

3.3.2: The impactsimpact 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). drivers, especially melting of land and sea ice (Sects.. 2.2 and 2.5). As outlined in Sect. 2.2, depending on the injection strategy, SAI may have limited effects on preventing the intensification and southward shift of the westerlies. It may thus fail to revert land ice melt, which exacerbates AABW loss, but also sea ice loss, which allows wider open stretches for convection and AABW formation (Sect. 3.3.1).

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,. Given large uncertainties and thus a judgement heere is impossible to make.the fact that SRM may affect various drivers in ways that may counteract each other, we cannot predict the sign of the overall effect. We also have no evidence as to whether SRM could reverse AABW tipping. once started

3.2.3: Further Research

Better understanding how and whetherof processes determining AABW can tip will beformation, and reducing model uncertainty, is key. Given the dependence on Antarctic Ice Meltice 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 Windswinds and the teleconnections that drive them may also be important if these prove to be influential in driving long-term trends of AABW formation.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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).(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).(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)Schneider, Kaul and Pressel (2019) predictingfinding 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). in their highly idealised setup.

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).(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).(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).(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)(Bretherton and Wyant, 1997).

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Using a cloud-resolving Large Eddy Simulation of a patch of marine stratocumulus coupled to a tropical atmospheric column model, Schneider et al. (2019)Schneider, Kaul and Pressel (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 °Ca substantial local and global warming, as such they found that. As the feedbacks associated with this warming make it more difficult for these clouds to form, this transition exhibited considerable hysteresis, with CO_2 concentrations neededneeding to be brought back below 300 ppm for the system to return to the cloudy state. Salazar and Tziperman (2023)Salazar and Tziperman (2023) reproduced this hysteresis in an idealizedidealised 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)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)(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)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.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Some support for this conclusion on the effects of this residual warming can be found in the sensitivity tests of Salazar and Tziperman (2023).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 from their model, breaking the association between temperature and emissivity in the inversion layer, and find 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)(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.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.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

5: Biosphere

5.1: The ~~Impact~~Impacts of SRM on ecological systems in general

Tipping points ~~in ecology can~~have been extensively discussed in the ecological literature (Jiang, Hastings and Lai, 2019), and ecological systems in the tipping literature (Lenton *et al.* 2023). Ecologists refer to tipping points for complete system changes either in the dominant~~ plant~~, foundational or keystone species, in the life forms or functional types of the plants (e.g. from trees to grasses), to large changes in the community of organisms present (e.g. 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~~the ecological literature refers to tipping points not only with respect to such changes at the system level~~,~~ (which we focus on here), but also ~~in~~to the point at which the extinction of an individual species~~.~~ becomes inevitable (Osmond and Klausmeier, 2017). Such changes may be driven by self-sustaining drivers and positive feedbacks, or to sudden or persistent drivers without positive feedbacks~~.~~ (Fig. 1).

~~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~~The losses of biodiversity locally, regionally 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~~globally 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~~ last half century, accelerating in recent years, has particularly focused attention on 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.~~

resulting in biological losses. Ecological systems are typically driven over tipping points by a complex series of drivers - including non-climatic drivers (Lenton *et al.* 2023) - rather than single dominant

Formatted: Font: 14 pt

Formatted: Font: 14 pt

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

drivers from local to global spatial scales, 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~~ (Liang *et al.*, 2022). Greater uncertainty of knowledge of climate impacts at ~~this scale~~local and regional scales 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~~ difficult, and exploitation and land-use change, amongst other anthropogenic factors, can interact to 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.~~climate-driven tipping.

There has been very little research on the impacts of SRM on complex ecosystems. The clearest clues as to whether SRM can prevent ecological tipping points ~~lies~~lie in its central role of reducing global average 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~~temperature-forced 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 net primary productivity may be more affected by more ~~organism-focused temperature related factors~~specific aspects of weather and climate that directly impact organisms. These may include extreme heat, which is generally reduced by SRM ~~(Kuswanto *et al.*, 2022)~~(Kuswanto *et al.*, 2022), ~~a~~ loss of ~~extreme cooling~~freezing temperatures and increase in nighttime temperatures, which are reduced substantially, but not fully, ~~compared to same-temperature mitigation scenarios by SRM (Zarnetske *et al.*, 2021)~~by SRM (Zarnetske *et al.*, 2021) ~~as well as~~and other factors ~~for which we have very limited evidence for the impact of SRM on, such as the~~including growing season duration, consecutive days of ~~growing seasons, the duration of continuous freezing~~extreme temperatures~~,~~ , and 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).~~(Zarnetske *et al.*, 2021). Thus even for the factor where we best understand the climatic

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

effects of SRM, the effects on ~~ecological systems~~pulling them back from, or pushing them over, tipping points, 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 (Ricke *et al.*, 2023) preclude a simple answer as to whether a SRM scheme would alleviate or exacerbate hydrological-related drivers of tipping. ~~Targeted efforts~~ It will be critical to ~~examine individual ecological systems for their~~understand both observed and modelled ecological responses to changes in ~~hydrological variables relative to predicted changes resulting from~~ precipitation and atmospheric drought (e.g. vapour pressure deficit) for SRM ~~schemes are critical before we can predict thresholds for hydrological~~scenarios to better anticipate changes that can drive or prevent ecological 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~~may remain high or rise, ~~which have~~with profound impacts on terrestrial and marine ecosystems ~~(Zarnetske *et al.*, 2021) . Moreover, the diffuse~~(Zarnetske *et al.*, 2021). Diffuse to direct light ~~ratio~~ratios would be ~~possibly~~ enhanced under SRM, potentially enhancing or otherwise altering photosynthesis ~~(Xia *et al.*~~for photosynthetic organisms (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~~

Other 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 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.~~

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Underline

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

~~In general,~~ besides average global 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 have profoundly ~~impact~~ different impacts on 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~~. 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~~and then be suddenly terminated while CO_2 continued to increase, ~~it is well established that~~ the termination effects on ecological systems ~~(Ito, 2017; Trisos *et al*., 2018)~~(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~~ , as many of these are examples of rate-dependent tipping (Fig. 2). The latitude(s) of injection sites would influence many aspects of climate relevant to potential ecological tipping points, including movement of the Hadley cells ~~(Smyth, Russotto and Storelvmo, 2017; Cheng *et al*., 2022)~~and the arctic-to-tropic temperature gradient (Smyth, Russotto and Storelvmo, 2017; Cheng *et al*., 2022).

5.2: ~~Dipterocarp~~Tropical 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.~~

Formatted: Subscript

Formatted: Font: 16 pt

Formatted: Font: 16 pt

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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,

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

~~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~~Rainforest Collapse

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)~~(Armstrong McKay *et al.*, 2022), regulating regional and even global climates (Wunderling *et al.*, 2024) 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).~~(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~~6^{O}C of global warming (relative to preindustrial), ~~interacting~~and even less when considering interactions with other human activities such as clearcutting and fires, ~~would likely~~might force a tipping point for the Amazon basin to the replacement of tropical forest with ~~tropical savanna~~systems without trees or ~~grassland.~~with fewer, scattered trees and without continuous canopies (Lenton *et al.* 2023). 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.*~~(Wunderling, Staal, *et al.*, 2022).

5.~~3~~2.1: Drivers and Feedbacks

~~The major~~As is the case for most highly diverse tropical forests globally (e.g., the Dipterocarp forests of Southeast Asia, SI), the forests of the Amazon are affected by multiple interacting factors that together may precipitate tipping. The major climatic 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).~~(Wunderling, Staal, *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)~~(Jiménez-Muñoz *et al.*, 2016; Costa *et al.*, 2022) that cause tree and animal mortalities either directly or indirectly through increased

Formatted: Heading 2

Formatted: Font color: Black

Formatted: Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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~~be significant in tipping. For example, (Zemp *et al.*, 2017) illustrating 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. ~~-~~(Staal *et al.*, 2020) further delineated a bistable state of forests in the southern Amazon, which are most susceptible to the drought-dieback feedback loop that would tip these forests to a savanna-like non-forested state.

~~Even if the conditions shift from those favouring savannah, it~~Fire is ~~possible that forest cover may remain for some time due to the micro-~~another major driver of tipping, driven by climatic ~~conditions that forests support; however, if drying~~and non-climatic sources, which is ~~so severe that wet season rains cannot replenish soil moisture, dieback is likely to occur. However,~~raised in significance if micro-climatic inertia is ~~significant, then the role of fire would be elevated in importance in tipping~~important ~~(Malhi *et al.*, 2009). Large parts of the Amazon have become increasingly flammable during drier months, although ignition sources are often scarce.~~(Malhi *et al.*, 2009). The increase in human activity and forest fragmentation~~, however,~~ increases the proximity of much of the forest to anthropogenic ignition points, ~~further~~which as the forest dries is the limiting factor in fire frequency, increasing the likelihood of ~~hitting a~~ tipping ~~point (Malhi *et al.*, 2009).~~(Malhi *et al.*, 2009). The impact of deforestation and degradation is the final significant driver of tipping (Lenton *et al.*, 2023), which not only causes increased vulnerability to other tipping drivers ~~(Wunderling *et al.*, 2022)~~(Wunderling, Staal, *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)~~(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)~~(Rietkerk *et al.*, 2021); it is unknown how SRM would enhance or detract from this resilience, so these will not be discussed further.

Formatted: Font: Arial, 11.5 pt, Font color: Blue

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Some changes in oceanic and atmospheric circulations due to climate change could also have indirect, beneficial effects on the resilience of Amazon forests. For example, the possible AMOC collapse with elevated warming (Sect. 3.1) is projected to shift the Intertropical Convergence Zone southwards (Orihuela-Pinto, England and Taschetto, 2022) and cause increased rainfall and decreased temperature in most parts of the Amazon, which would stabilise eastern Amazonian rainforests (Nian *et al.*, 2023) by mitigating the above-mentioned drought-dieback feedback loop.

5.~~3~~2.2: The ~~impacts~~impact of SRM

The ~~effect~~paucity of research makes predicting the effects 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)~~(Carvalho *et al.*, 2023). ~~Firstly,~~We know that 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~~large-scale impacts of SRM, but tropical forests commonly depend not only on global circulation patterns, but also may depend on regional changes including monsoon dynamics and convection-forest interactions, which are not yet often accurately captured in models~~.~~ (indeed, GCMs often disagree on even the sign of these regional precipitation change). 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).~~(Fan *et al.*, 2021). Changes in relative humidity and vapour pressure deficit are also important for forest function ~~(Grossiord *et al.*, 2020)~~(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).~~(Fan *et al.*, 2021). Whether global warming is increasing land aridity or not is a highly debated topic ~~(Berg and McColl, 2021)~~(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~~Moreover, effects may be in different directions; for example, given SRM could stabilise the AMOC (Sect. 3.1.2), this would aid the tipping process, even when other effects may help prevent it. Because SRM would not reverse 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

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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)~~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)~~(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)~~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),~~(Malhi *et al.*, 2009), so in our overall judgement we have weighted the impact of SRM on this region higher, 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,~~ so the effect SRM has on Amazon tipping remains highly uncertain. Moreover, SRM does not affect deforestation or the proximity of the rainforest to ignition sources, which are key drivers of tipping.

5.~~3~~2.3: 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

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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,Better monitoring of and incorporating spatial data on land use change in the Amazon basin and more widely in tropical forests globally is essential for realistic predictions; 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). (Carvalho *et al.*, 2023). Better understanding of the relationship between phylogenetic diversity and plant functional traits, and their heterogeneity across the Amazon Basin will facilitate more accurate predictions of responses to climate change and the effects of SRM in promoting or reducing incipient tipping points. 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. –Furthermore, better understanding the importance of droughts and fires in different regions to overall Amazon dieback, may allow us to constrain the effect of the differential regional impacts of SRM on the tipping element as a whole.

5.43: 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).(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.*(Jouffray *et al.*, 2019).

5.43.1: 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

Formatted: Font color: Black

Formatted: Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

will expel their symbiotic photosynthetic dinoflagellates; if they are bleached for extended periods of time, this can result in death ~~(Wang *et al.*, 2023). If the corals are~~ (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~~.~~ (Schmitt *et al.*, 2019). 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).~~(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.*~~(Holbrook *et al.*, 2016).

Acidification ~~also~~ is a secondary driver of tipping. ~~As CO_2 levels increase and~~As more CO2 dissolves in ocean water~~, the CO2 reacts with water to form a mild acid. As~~ aragonite saturation levels drop, so 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).~~(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.*~~(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~~(Gardner *et al.*, 2005; Mudge and Bruno, 2023). 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~~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)~~(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. -Moreover, diseases (Alvarez-Filip *et al.*, 2022) and invasive species (Pettay *et al.*, 2015), often associated with warming and global trade, also have negative impacts on the structure, functioning and stability of coral reefs such as those found in the Caribbean.

Formatted: Font color: Black

Formatted: Font color: Black

Field Code Changed

Formatted: Font color: Black

Formatted: Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

5.~~4~~3.2: The ~~impacts~~impact of SRM

SRM would ~~likely~~ help to reduce ~~-~~coral reefs tipping by reducing ocean temperatures ~~(Couce *et al.*, 2013)~~(Couce *et al.*, 2013), thus likely 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)~~(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)~~(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)~~(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)~~(Jones *et al.*, 2017; Wang, Moore and Ji, 2018).

The impact of SRM on the incoming radiation, both by reducing the amount of direct radiation and increasing the diffuse ~~fraction~~radiation, is also likely to impact photosynthesis but any effect on tipping behaviour of photosynthetic organisms is likely to be ~~minor and have~~ minimal ~~impacts on tipping behaviour.~~due to the cancellation effects between direct and diffuse radiation changes induced by SRM (Shao *et al.*, 2020; Durand *et al.*, 2021; Fan *et al.*, 2021). These studies, however, were carried out in terrestrial environments, so the effect on phytoplankton may be different. Non-climatic or CO_2 related anthropogenic drivers will be unaffected by SRM.

~~(Couce *et al.*, 2013)~~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)~~Zhang, Jones and James (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

Formatted: Line spacing: single

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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~~report an undercompensation 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).~~(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~~3.3 Further Research

Given the high level of temperature dependence of the climatic drivers, our understanding of the direction 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.~~ than other tipping elements. Nonetheless, the lack of modelling studies, combined with the presence of uncertainties (such as the difference in SRM impact across regions) and co-drivers alongside temperature (such as bleaching) might indicate that up-to-date ESM studies of SRM's impact on coral reefs would be useful. Studies of how much SRM might be necessary and what deployment design is needed to keep below critical thresholds of Degree Heating Week and recurrence times, as well as the impacts on storm intensity would be useful too. We also lack the understanding whether reducing the temperature driver is sufficient to stop tipping if other drivers of tipping are severe enough. The interest in regional MCB to avoid tipping would also require further research to test if proposed schemes are feasible. 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~~4: The Himalaya-to-Sundarbans (HTS) Hydro-ecological System

Formatted: Font: Times New Roman, 12 pt

Formatted: Font: Bold

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

The HTS system extends from the glaciers of the Himalaya to the Sundarbans in the Bay of Bengal. This large, integrated subcontinental system, is poorly understood and understudied and is an important but underappreciated component of the Earth System. The HTS hydro-ecological system is a plausible candidate as a regional impact tipping element (as established in (Lenton *et al.*, 2008) and Armstrong McKay *et al 2022*). The ecological systems are dependent on the interconnections between the glacial-riparian network originating from Himalayan glaciers, the monsoon, and on the interface between the marine and terrestrial environments at the deltas where the Ganges, Brahmaputra and Meghna Rivers converge in the Sundarbans. The melting of the montane glaciers, changes to the monsoon and sea level rise are already pushing this complex system to unprecedented new states (Negi *et al.*, 2022), although whether tipping in the strict sense occurs has yet to be proven. We chose the HTS system to highlight the potential for SRM to impact more complex and multilayered ecological systems which show some plausibility of tipping, although considerably more work is needed to confirm this hypothesis.

The HTS includes major elements of the cryosphere, the atmosphere (particularly the monsoon but also cyclonic storms), the boundary between marine and terrestrial systems, and ecological systems from alpine tundra to temperate and tropical forests, and enormous and complex riparian systems and wetlands. Like the many different forest types in the Amazon Basin, and the heterogeneity within and among coral reefs and the northern coniferous forests, the HTS system is a heterogeneous mosaic. Tipping to alternative states is already occurring and will accelerate with climate change, with degradation of native and endemic species diversity (Negi *et al.* 2022), changes in species distribution (Telwala *et al.*, 2013), increasing dominance of invasive pan-global species adapted to high levels of disturbance, and global decreases in cold-tolerant and cold-adapted species. These system changes will be integrated with biogeochemical changes, with implications for future climate through complex impacts on albedo, hydrological cycles, runoff, and other changes.

Whether SRM would have positive or negative implications for tipping the HTS system is not well understood but we analyse the probabilities below according to what is known about these systems and the projections for SRM. The HTS system is topographically highly complex, ranging from Earth's highest mountains to sea level at the Bay of Bengal, and supports a substantial proportion of Earth's biodiversity hotspots

Several. It includes the biodiversity hotspots are found on the Indian subcontinent, includingencompassing the eastern Himalaya/southwestern China (Sharma *et al.*, 2009)(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,

Formatted: Font: 12 pt

Formatted: Space Before: 12 pt, Line spacing: Multiple 1.15 li

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

~~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 complex and diverse 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.~~(Sect. 2.3).

~~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.~~

Higher temperatures and erosion due to increasingly intense rainstorms resulting from global climate change could potentially tip this system from a mosaic of biodiverse alpine systems, temperate and tropical forests, woodlands vast wetlands with many endemic species to a monotonous and depauperate structure dominated by invasive grass and shrub species.

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~~at 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, extensive river damming, and the failure of river water supply from the Himalaya 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)~~(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~~4.1: Drivers and Mechanisms

There are a number of potential climate change-induced drivers of tipping ~~points~~ in the ~~Indian subcontinent~~HTS system, including melting montane glaciers, extreme flooding, changes in the Hadley cells and the monsoon, sea level rise, droughts and extreme high temperatures ((Swapna *et al.*, 2017; Mishra, Aadhar and Mahto, 2021; Mall *et al.*, 2022). Severe and extended heat in this region in recent years, exacerbated by drying, is likely to directly affect organism survival, species abundances and lead

Formatted: Space Before: 12 pt, Line spacing: Multiple 1.15 li

Formatted: Font: Bold

Formatted: Font: Bold

Formatted: Normal, Space Before: 12 pt, Line spacing: Multiple 1.15 li

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

to extinctions, pushing some natural systems over tipping points (Mishra et al., 2020). (Im, Pal and Eltahir, 2017) predicted that extreme heatwaves (Swapna *et al.*, 2017; Mishra, Aadhar and Mahto, 2021; Mall *et al.*, 2022). would exceed the human survivability limit (35^{O}C wet-bulb temperature) at a few locations in the densely populated agricultural regions of the Ganges and Indus river basins and would approach the survivability limit over most of South Asia under the RCP8.5 scenario by the end of the century (i.e., about 4.5 degrees Celsius warming relative to preindustrial). Global warming is also melting high elevation glaciers rapidly worldwide (Sect. 2.3) (Hugonnet *et al.*, 2021).(Hugonnet *et al.*, 2021), with accelerated ice loss observed across the Himalayas over the past 40 years (Maurer *et al.*, 2019) and a likely non-linear increasing trend with greater than 3 degrees Celsius warming (Rounce *et al.*, 2023). Glacial melting in the Himalaya (Potocki *et al.*, 2022)(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 subcontinentHTS system, including the Ganges-Brahmaputra-Meghna basin below dependent on themthese glaciers as a source of water. Changes to the in the distribution, intensity and timing of tropical monsoonal rains in the Indian subcontinentHTS (Varikoden *et al.*, 2019) are also potential tipping points (Armstrong McKay *et al* 2022),drivers of in tipping the ecological, agricultural, and human systems that depend on them. The ecological systems of the Western Ghats are particularly in the Western Ghats.vulnerable to tipping to an alternative, unknown state if there should be a failure of the monsoon. Climate change has been implicated in failure of the monsoon in parts of the subcontinent (Swapna *et al.*, 2017)HTS (Swapna *et al.*, 2017), and extreme rainfall events and severe flooding in other parts, with catastrophic change to some natural and agricultural systems. Climate induced sea level rise, exacerbated by extensive river damming, is contributing to the tipping of the vast coastal mangrove systems that are an integral part of the HTS system. There also exist significant non-climate related drivers of tipping in this system, particularly deforestation (Pandit *et al.*, 2007).

5.5.4.2: The impactsimpact of SRM

SRM's cooling is expected toClimate-related drivers of tipping for the complex HTS system that would be affected by SRM are extreme heat, glacial melting, intense rainfall and other monsoonal change, and rising sea levels. Reduction of the extent and severity of extreme heat from the implementation of SRM can therefore potentially prevent heat-related deaths and extinctions, preventing system tipping points from occurring. SRM would also partially 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.pulling components of the HTS system back from tipping. While SRM might relieve the likelihood of hitting tipping points caused by extreme rainfall events 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).

Formatted: Font: 13 pt, Bold

Formatted: Font: 13 pt, Bold

Formatted: Font: 13 pt, Bold

Formatted: Normal, Space Before: 12 pt, After: 12 pt, Line spacing: Multiple 1.15 li

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

~~Even~~ changes in the seasonality and predictability of the monsoons ~~could force flash droughts (Mishra, Aadhar and Mahto, 2021) and related tipping in~~ , leading to drought-induced tipping (Smyth, Russotto and Storelvmo, 2017; Cheng *et al.*, 2022; Mishra, Aadhar and Mahto, 2021). Eventual and partial reductions in sea level rise due to cooling from SRM, and restoration of riparian freshwater from restoration of glaciers, might have 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~~restorative effects in pulling the mangrove forests ringing the Bay of Bengal back from tipping. However, the anthropogenic effects of damming and other land use changes would reduce these potential reversals of tipping for this part of the HTS system.

5.~~5~~4.3: Further research

Research directions to better understand the potential impact of SRM on the ~~Indian subcontinent biodiversity hotspots~~HTS earth system element largely overlap with progress in research on mountain cryosphere, sea level rise and extreme events. ~~But ecological~~While aspects of this system have been studied, much more work on the nature of the complex integrated networks that comprise this system will be critical not only for understanding the HTS, but as a model for understanding other large systems that integrate major Earth System, biological, and human dimensions. 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~~). These human actions could exacerbate the risks of collapsing or tipping. Therefore, the ~~time~~timing and ~~threshold~~thresholds of tipping in these biodiversity hotspots and how ~~they~~these will respond to climate change and SRM ~~should deserve more~~requires collaborative research between climatologists, ecologists and biologists. Far greater awareness of this overlooked but major earth system element among scientists and the general public is also critically needed.

5.~~6~~5: Northern ~~Coniferous~~Boreal 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~~

Formatted: Font: Bold

Formatted: Font: Bold

Formatted: Normal, Space Before: 12 pt, Line spacing: Multiple 1.15 li

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

~~Barry, 2011)~~(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)~~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).~~(Berner and Goetz, 2022). Rao *et al.* (2023) found that climate change is predicted to expose a foundational and dominant tree species across the entire region, *Larix siberica*, to temperatures that result in irreversible damage to photosynthetic tissue in the near future, leading to widespread and abrupt synchronous tree mortality. Tree mortality at this extent would be likely to cause a tipping point for the entire southern boreal forest system to a grassland-steppe system, as has been already observed in some areas (W. Li *et al*., 2023). They suggest that an abrupt tipping point may be reached within the next decades which would “fundamentally and irreversibly alter the ecosystem state at regional to sub-continental spatial scales” for hundreds of km along an extensive area in the southern Eurasian boundary of the northern coniferous forests.

5.~~6~~5.1: Drivers and ~~Mechanisms~~Feedbacks

Warmer temperatures, increased evaporative demand, increased droughts, lower water availability and reduced snowpack and duration of snowpack under climate change ~~both~~all 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 (Armstrong 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~~(Bentz *et al*., 2010). The effects on feedbacks to climate are complex and difficult to predict. Reduced duration of snow cover 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).~~. A tipping

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

point leading to a shift from boreal forest to grassland/steppe might potentially increase albedo, at least during the growing season. Extensive fires and decomposition of soil carbon stores resulting from melting of permafrost would greatly decrease carbon storage and contribute to increases to atmospheric carbon and global warming (Ruiz-Pérez and Vico 2020). Thus dieback can have opposite regional (cooling by increased albedo) and global (warming by carbon release) climatic effects. These dynamics could interact in complex stochastic ways, with potential for positive feedbacks. Other climate elements that can lead to tipping in this system include melting of permafrost (Sect. 2.6).

5.~~6~~5.2: ~~Impact~~The impacts of SRM

~~By having~~As far as the authors know, there are no specific studies on the impact of SRM on boreal forests. By cooling average temperatures, it is possible that the consequences of SRM for 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~~are likely to 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. Preservation of cold temperatures and prevention of extreme heat events could prevent widespread mortality of Larix and other foundational tree species in the boreal forest, likewise pulling it back from a tipping point from forest to steppe. By reducing the frequency and extent of boreal forest wildfires, reductions in heat could also reduce the positive feedbacks between loss of carbon stores in living trees and soil organic matter and the carbon in the atmosphere. Furthermore, given complex eco-hydrological mechanisms in boreal forest dynamics, the large uncertainty in simulated regional precipitation changes under SRM might complicate the above temperature-driven mechanisms of tipping dynamics (see more discussions on this aspect in Sects. 1.1 and 5.2).

5.~~6~~5.3: Further research

Research explicitly of the impact of SRM on boreal forests is needed. 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

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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.~~

Formatted: Font: 16 pt

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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 Insufficent)	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

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

[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

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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

6.1 Conclusions

Our review suggests that for 10 out of 15 tipping elements considered, spatially homogeneous peak-shaving (Section 1.2) SRM would be at least partially effective in reducing their drivers, while for 3 we could not determine the sign of SRM's impact due to low process understanding. AMOC was the only tipping element where we judged SRM to possibly overcompensate the effect of climate change on the drivers. 2 of the tipping elements (AMOC included) the effect of SRM was at a minimum not compensating the effect of climate change. For none of the tipping elements was it expected that SRM may worsen the overall effects of the drivers, although for some their drivers were worsened (Table 1, Fig. 3). Moreover, regional heterogeneities may be significant; for example, for the Western Amazon, the overall effect was W-P, but this is less significant for tipping than the effect on the Eastern Amazon, hence the overall judgement of the effect on tipping was N-P. Uncertainties are considerable to very large for the vast majority of tipping elements, particularly those where the drivers were less strongly coupled to global temperature. Moreover, our analysis has largely relied on qualitative judgement based on process understanding, so these should mostly be considered as evidence-backed hypotheses needing further research.

Although rate-dependence effects could play a role for some ecological tipping elements and potentially AMOC, for most tipping elements the level and (for slowly-evolving systems like ice caps) the duration of drivers, rather than their rate of change, determines whether the system tips. This implies that preventing tipping would require SRM to be in place until other measures, such as negative emissions, can reduce the strength of the tipping drivers - merely slowing down the rate of warming would at most postpone tipping. Absence of rate-dependence may also imply that a "termination shock" from discontinuation of SRM would not affect tipping probability for most tipping elements.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Deliberately using SRM to reverse self-sustained tipping dynamics, once started, may be more difficult than reducing drivers preventatively, for several reasons. First, it may require stronger forcing, not be physically possible for many tipping elements (Table 1), or reversal may still exhibit considerable hysteresis. Second, process understanding is weaker than for drivers, making it harder to judge the correct dose, or timing, of the intervention; in particular, reliable early-warning-signals may not be available for most tipping points. Whilst it may be possible for some tipping elements to be 'pulled back from the brink' by 'emergency deployment' of SRM soon after tipping has begun, this strategy appears risky and ill-advised. Thus, we conclude, like Lenton (2018), that such a strategy ought not to be relied upon to reduce the tipping risk, and instead we suggest that the most feasible role (if any) for SRM would be preemptive deployment preventing hitting tipping elements rather than reversal once they have been hit.

6.2 Uncertainties

Physical uncertainties for individual tipping elements were discussed in specific sections above. Some stem from limited process understanding of tipping elements involved, e.g. regarding threshold values for driver intensity and duration, the relative importance of and possible interaction between drivers, and the dynamics of the tipping process once initiated. Climate models notoriously struggle to represent tipping behaviour, partly because relevant processes and/or subsystems are not included in models, partly due to model uncertainties and biases.

SRM introduces an additional layer of uncertainty, namely, regarding its effect on tipping drivers and feedbacks. It is often possible to obtain a reasonable estimate of SRM's effect on drivers, especially if they are temperature-driven, although sometimes the drivers less coupled to temperature (e.g. precipitation in the Amazon) are much harder to predict, and introduce much more uncertainty into our estimates. Feedbacks are often even less well understood, and the estimate for the effect of SRM on these are often even more uncertain. Direct climate simulations are typically lacking, either because the tipping process itself is not well represented, or because dedicated simulations with SRM have not been performed. In some cases, proxies can be used (e.g. modelled AMOC weakening for potential AMOC tipping).

Scenario uncertainty arises because the effect of SRM is most likely dependent on the implementation strategy (e.g., type and location of SRM) and it's time trajectory. Our assessment is based on a spatially fairly homogeneous peak-shaving scenario, but spatially inhomogeneous cooling and associated

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

circulation changes may have strong beneficial or adverse local impacts, while delaying SRM use may mean that some tipping points are already breached.

Political uncertainties are arguably the most concerning uncertainties around SRM. We will only highlight a few that might affect SRM's ability to prevent tipping - the discussion of whether a potential reduction in tipping risk (or other climate risks) is worth incurring political risks from SRM is important, but beyond the scope of this study. Mitigation deterrence (McLaren, 2016), if actually relevant (Cherry *et al.*, 2023), might mean that SRM leads to higher GHG concentrations than if it had never been deployed. This could exacerbate tipping risks, especially if negative emissions turn out to be difficult, and/or if SRM cannot be sustained at the required intensity for long enough to avoid temperature overshoot. International disagreement on SRM may lead to inconsistent or suboptimal implementation that could be delayed, of variable or insufficient intensity, or include a host of local to regional measures that interact with tipping points in potentially unpredictable ways. Moreover, large scale CDR required to achieve the CO_2 concentration reductions needed in a 'peak-shaving' scenario may put significant pressure on ecosystems. In those scenarios, whilst SRM may help avoid tipping in the ecosystem, the effect of the overall SRM and CDR package may be more equivocal.

6.3 Research recommendations

The wider climate science community will hopefully continue to work towards better process understanding of tipping, including better representation thereof in models. In the short run, a systematic assessment on (the relative importance of) tipping drivers may be helpful. Where applicable, this can be done with subsystem models (e.g., ice sheet models) if relevant processes are not included in global Earth System Models.

For many non-SAI techniques, uncertainties regarding their effectiveness and/or technical feasibility (including the time of earliest possible deployment) remain large, yet those parameters are vital for potentially suppressing tipping. The SRM community should continue to address these questions. In addition, SRM's effect on relevant tipping drivers, especially those less closely coupled to temperature, should be systematically assessed in existing and new SRM simulations.

For tipping points that are reasonably well represented in models, dedicated simulations of SRM's effect on preventing or reversing tipping should be performed. If model uncertainties are still large, strong SRM and GHG forcing can be used to explore whether certain processes are possible "in principle", whereas in the course of time, more modest and/or realistic forcing scenarios can be studied.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Direct simulation of preventing or reversing tipping may not yet be feasible for tipping elements that are not well represented in models.

A challenge is the huge number of possible SRM scenarios, which may vary on background GHG trajectories, SRM method (SAI or other; possibly combinations) and location, starting year, intensity, and so on. The choice of scenario may depend on the underlying research question, for example: Can (and should) SRM be optimised? Are there low-regret options? Can (ill-coordinated) implementation exacerbate tipping risks? Communication with social scientists and stakeholders can help prioritise research questions.

Our preliminary assessment suggests that well-implemented SRM may have an overall beneficial effect on many Earth System tipping elements, although uncertainties are still very large. Whilst tipping concerns are 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~~ and ought to be a part of any assessment of the ~~impacts~~benefits and risks 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~~, such an assessment ~~of the impact of SRM on them. This effort is also ongoing.~~

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

~~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 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~~must be holistic and consider 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~~concerns alongside other climatic, ~~ecological~~environmental, 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~~factors that are affected by SRM.

Formatted: No underline

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

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.
Overall lead and coordination: GF with input from CW
Conceptualisation and methodology: GF with input from CW
Introduction: CW with assistance of GF and JG
Section 2.1 to 2.4: MA under the supervision of PI
Section 2.5-2.8: AD under the supervision of PI
Section 3: CW
Section 4: PI
Section 5: YF and JG (with GF on Section 5.2 and 5.3)
Discussion: GF and CW
Reviewing of all sections: GF

Competing Interests

The authors declare that they have no conflict of interest.

References

Alley, R.B. *et al.* (2015) 'Oceanic Forcing of Ice-Sheet Retreat: West Antarctica and More', *Annual review of earth and planetary sciences*, 43(1), pp. 207–231.

Applegate, P.J. and Keller, K. (2015) 'How effective is albedo modification (solar radiation management geoengineering) in preventing sea-level rise from the Greenland Ice Sheet?', *Environmental research letters: ERL [Web site]*, 10(8), p. 084018.

Archer, D., Buffett, B. and Brovkin, V. (2009) 'Ocean methane hydrates as a slow tipping point in the global carbon cycle', *Proceedings of the National Academy of Sciences of the United States of America*, 106(49), pp. 20596–20601.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Armstrong McKay, D.I. *et al.* (2022) 'Exceeding 1.5°C global warming could trigger multiple climate tipping points', *Science*, 377(6611), p. eabn7950.

Aschwanden, A. *et al.* (2019) 'Contribution of the Greenland Ice Sheet to sea level over the next millennium', *Science advances*, 5(6), p. eaav9396.

Ashwin, P. *et al.* (2012) 'Tipping points in open systems: bifurcation, noise-induced and rate-dependent examples in the climate system', *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, 370(1962), pp. 1166–1184.

Bas, M.A. and Mahajan, A. (2020) 'Contesting the climate', *Climatic change*, 162(4), pp. 1985–2002.

Bassis, J.N. and Walker, C.C. (2011) 'Upper and lower limits on the stability of calving glaciers from the yield strength envelope of ice', *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 468(2140), pp. 913–931.

Bathiany, S. *et al.* (2016) 'On the Potential for Abrupt Arctic Winter Sea Ice Loss', *Journal of climate*, 29(7), pp. 2703–2719.

Bednarz, E.M. *et al.* (2022) 'Impact of the latitude of stratospheric aerosol injection on the southern annular mode', *Geophysical research letters*, 49(19). Available at: https://doi.org/10.1029/2022gl100353.

Beisner, B.E. and Haydon, D.T. (2003) 'Alternative stable states in ecology', *Frontiers in ecology and the environment* [Preprint]. Available at: https://doi.org/10.1890/1540-9295(2003)001[0376:ASSIE]2.0.CO;2.

Bellamy, R. (2023) 'Public perceptions of climate tipping points', *Public understanding of science* , p. 9636625231177820.

Bellon, G. and Geoffroy, O. (2016) 'Stratocumulus radiative effect, multiple equilibria of the well-mixed boundary layer and transition to shallow convection', *Quarterly Journal of the Royal Meteorological Society*, 142(697), pp. 1685–1696.

Bentz, B.J. *et al.* (2010) 'Climate Change and Bark Beetles of the Western United States and Canada: Direct and Indirect Effects', *Bioscience*, 60(8), pp. 602–613.

Berdahl, M. *et al.* (2014) 'Arctic cryosphere response in the geoengineering model intercomparison project G3 and G4 scenarios', *Journal of geophysical research*, 119(3), pp. 1308–1321.

Berg, A. and McColl, K.A. (2021) 'No projected global drylands expansion under greenhouse warming', *Nature climate change*, 11(4), pp. 331–337.

Berner, L.T. and Goetz, S.J. (2022) 'Satellite observations document trends consistent with a boreal forest biome shift', *Global change biology*, 28(10), pp. 3275–3292.

Biskaborn, B.K. *et al.* (2019) 'Permafrost is warming at a global scale', *Nature communications*, 10(1), p. 264.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Bitz, C.M. and Roe, G.H. (2004) ‘A Mechanism for the High Rate of Sea Ice Thinning in the Arctic Ocean’, *Journal of climate*, 17(18), pp. 3623–3632.

Boers, N. *et al.* (2017) ‘A deforestation-induced tipping point for the South American monsoon system’, *Scientific reports*, 7, p. 41489.

Böning, C.W. *et al.* (2016) ‘Emerging impact of Greenland meltwater on deepwater formation in the North Atlantic Ocean’, *Nature geoscience*, 9(7), pp. 523–527.

Born, A. and Stocker, T.F. (2014) ‘Two Stable Equilibria of the Atlantic Subpolar Gyre’, *Journal of physical oceanography*, 44(1), pp. 246–264.

Bretherton, C.S. and Wyant, M.C. (1997) ‘Moisture Transport, Lower-Tropospheric Stability, and Decoupling of Cloud-Topped Boundary Layers’, *Journal of the Atmospheric Sciences*, 54(1), pp. 148–167.

Brienen, R.J.W. *et al.* (2015) ‘Long-term decline of the Amazon carbon sink’, *Nature*, 519(7543), pp. 344–348.

Bronselaer, B. *et al.* (2018) ‘Change in future climate due to Antarctic meltwater’, *Nature*, 564(7734), pp. 53–58.

Bronselaer, B. *et al.* (2020) ‘Importance of wind and meltwater for observed chemical and physical changes in the Southern Ocean’, *Nature geoscience*, 13(1), pp. 35–42.

Brown, B.E. *et al.* (2019) ‘Long-term impacts of rising sea temperature and sea level on shallow water coral communities over a ~40 year period’, *Scientific reports*, 9(1), p. 8826.

Burke, E.J., Zhang, Y. and Krinner, G. (2020) ‘Evaluating permafrost physics in the Coupled Model Intercomparison Project 6 (CMIP6) models and their sensitivity to climate change’, *The Cryosphere*, 14(9), pp. 3155–3174.

Cao, L., Caldeira, K. and Atul, K.J. (2009) ‘Effects of carbon dioxide and climate change on ocean acidification and carbonate mineral saturation’, *Geophysical Research Letters* [Preprint]. Available at: https://doi.org/Alvarez-Filip, L. *et al.* (2022) ‘Stony coral tissue loss disease decimated Caribbean coral populations and reshaped reef functionality’, *Communications biology*, 5(1), p. 440.

Applegate, P.J. and Keller, K. (2015) ‘How effective is albedo modification (solar radiation management geoengineering) in preventing sea-level rise from the Greenland Ice Sheet?’, *Environmental research letters: ERL [Web site]*, 10(8), p. 084018.

Armstrong McKay, D.I. *et al.* (2022) ‘Exceeding 1.5°C global warming could trigger multiple climate tipping points’, *Science*, 377(6611), p. eabn7950.

Ashwin, P. *et al.* (2012) ‘Tipping points in open systems: bifurcation, noise-induced and rate-dependent examples in the climate system’, *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, 370(1962), pp. 1166–1184.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Bas, M.A. and Mahajan, A. (2020) ‘Contesting the climate’, *Climatic change*, 162(4), pp. 1985–2002.

Bassis, J.N. and Walker, C.C. (2011) ‘Upper and lower limits on the stability of calving glaciers from the yield strength envelope of ice’, *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, 468(2140), pp. 913–931.

Bathiany, S. *et al.* (2016) ‘On the Potential for Abrupt Arctic Winter Sea Ice Loss’, *Journal of climate*, 29(7), pp. 2703–2719.

Bednarz, E.M. *et al.* (2022) ‘Impact of the latitude of stratospheric aerosol injection on the southern annular mode’, *Geophysical research letters*, 49(19). Available at: https://doi.org/10.1029/2022gl100353.

Bellamy, R. (2023) ‘Public perceptions of climate tipping points’, *Public understanding of science* , p. 9636625231177820.

Bellon, G. and Geoffroy, O. (2016) ‘Stratocumulus radiative effect, multiple equilibria of the well-mixed boundary layer and transition to shallow convection’, *Quarterly Journal of the Royal Meteorological Society*, 142(697), pp. 1685–1696.

Bentz, B.J. *et al.* (2010) ‘Climate Change and Bark Beetles of the Western United States and Canada: Direct and Indirect Effects’, *Bioscience*, 60(8), pp. 602–613.

Berdahl, M. *et al.* (2014) ‘Arctic cryosphere response in the geoengineering model intercomparison project G3 and G4 scenarios’, *Journal of geophysical research*, 119(3), pp. 1308–1321.

Berg, A. and McColl, K.A. (2021) ‘No projected global drylands expansion under greenhouse warming’, *Nature climate change*, 11(4), pp. 331–337.

Berner, L.T. and Goetz, S.J. (2022) ‘Satellite observations document trends consistent with a boreal forest biome shift’, *Global change biology*, 28(10), pp. 3275–3292.

Bitz, C.M. and Roe, G.H. (2004) ‘A Mechanism for the High Rate of Sea Ice Thinning in the Arctic Ocean’, *Journal of climate*, 17(18), pp. 3623–3632.

Boers, N. *et al.* (2017) ‘A deforestation-induced tipping point for the South American monsoon system’, *Scientific reports*, 7, p. 41489.

Born, A. and Stocker, T.F. (2014) ‘Two Stable Equilibria of the Atlantic Subpolar Gyre’, *Journal of physical oceanography*, 44(1), pp. 246–264.

Bretherton, C.S. and Wyant, M.C. (1997) ‘Moisture Transport, Lower-Tropospheric Stability, and Decoupling of Cloud-Topped Boundary Layers’, *Journal of the Atmospheric Sciences*, 54(1), pp. 148–167.

Brienen, R.J.W. *et al.* (2015) ‘Long-term decline of the Amazon carbon sink’, *Nature*, 519(7543), pp. 344–348.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Bronselaer, B. *et al.* (2018) 'Change in future climate due to Antarctic meltwater', *Nature*, 564(7734), pp. 53–58.

Brown, B.E. *et al.* (2019) 'Long-term impacts of rising sea temperature and sea level on shallow water coral communities over a ~40 year period', *Scientific reports*, 9(1), p. 8826.

Burke, E.J., Zhang, Y. and Krinner, G. (2020) 'Evaluating permafrost physics in the Coupled Model Intercomparison Project 6 (CMIP6) models and their sensitivity to climate change', *The Cryosphere*, 14(9), pp. 3155–3174.

Cao, L., Caldeira, K. and Atul, K.J. (2009) 'Effects of carbon dioxide and climate change on ocean acidification and carbonate mineral saturation', *Geophysical Research Letters* [Preprint]. Available at: https://doi.org/10.1029/2006GL028605.

Carvalho, R.L. *et al.* (2023) 'Pervasive gaps in Amazonian ecological research', *Current biology: CB* [Preprint]. Available at: https://doi.org/Carvalho, R.L. *et al.* (2023) 'Pervasive gaps in Amazonian ecological research', *Current biology: CB* [Preprint]. Available at: https://doi.org/10.1016/j.cub.2023.06.077.

Chadburn, S.E. *et al.* (2017) 'An observation-based constraint on permafrost loss as a function of global warming', *Nature climate change*, 7(5), pp. 340–344.

Chen, G. *et al.* (2021) 'Elevation and volume changes in Greenland ice sheet from 2010 to 2019 derived from altimetry data', *Frontiers of earth science*, 9. Available at: https://doi.org/Chadburn, S.E. *et al.* (2017) 'An observation-based constraint on permafrost loss as a function of global warming', *Nature climate change*, 7(5), pp. 340–344.

Chen, G. *et al.* (2021) 'Elevation and volume changes in Greenland ice sheet from 2010 to 2019 derived from altimetry data', *Frontiers of earth science*, 9. Available at: https://doi.org/10.3389/feart.2021.674983..

Cheng, W. *et al.* (2022) 'Changes in Hadley circulation and intertropical convergence zone under strategic stratospheric aerosol geoengineering', *npj Climate and Atmospheric Science*, 5(1), pp. 1–11.

Chen, Y. *et al.* (2023) 'Northern-high-latitude permafrost and terrestrial carbon response to two solar geoengineering scenarios', *Earth system dynamics*, 14(1), pp. 55–79.

Chen, Y., Liu, A. and Moore, J.C. (2020) 'Mitigation of Arctic permafrost carbon loss through stratospheric aerosol geoengineering', *Nature communications*, 11(1), p. 2430.

Cherry, T.L. *et al.* (2023) 'Climate cooperation in the shadow of solar geoengineering: an experimental investigation of the moral hazard conjecture', *Environmental politics*, 32(2), pp. 362–370.

Comyn-Platt, E. *et al.* (2018) 'Carbon budgets for 1.5 and 2 °C targets lowered by natural wetland and permafrost feedbacks', *Nature geoscience*, 11(8), pp. 568–573.

Corry, O. (2017) 'The international politics of geoengineering: The feasibility of Plan B for tackling

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

climate change', *Security dialogue*, 48(4), pp. 297–315.

Costa, D.F. *et al.* (2022) 'The most extreme heat waves in Amazonia happened under extreme dryness', *Climate Dynamics*, 59(1), pp. 281–295.

Couce, E. *et al.* (2013) 'Tropical coral reef habitat in a geoengineered, high-CO2world', *Geophysical research letters*, 40(9), pp. 1799–1805.

DeConto, R.M. *et al.* (2021) 'The Paris Climate Agreement and future sea-level rise from Antarctica', *Nature*, 593(7857), pp. 83–89.

DeConto, R.M. and Pollard, D. (2016) 'Contribution of Antarctica to past and future sea-level rise', *Nature*, 531(7596), pp. 591–597.

Dias, F.B. *et al.* (2021) 'Subpolar Southern Ocean Response to Changes in the Surface Momentum, Heat, and Freshwater Fluxes under 2xCO2', *Journal of climate*, 34(21), pp. 8755–8775.

Dinniman, M.S., Klinck, J.M. and Hofmann, E.E. (2012) 'Sensitivity of Circumpolar Deep Water Transport and Ice Shelf Basal Melt along the West Antarctic Peninsula to Changes in the Winds', *Journal of climate*, 25(14), pp. 4799–4816.

Ditlevsen, P.D. and Johnsen, S.J. (2010) 'Tipping points: Early warning and wishful thinking', *Geophysical research letters*, 37(19). Available at: https://doi.org/Cheng, W. *et al.* (2022) 'Changes in Hadley circulation and intertropical convergence zone under strategic stratospheric aerosol geoengineering', *npj Climate and Atmospheric Science*, 5(1), pp. 1–11.

Chen, Y. *et al.* (2023) 'Northern-high-latitude permafrost and terrestrial carbon response to two solar geoengineering scenarios', *Earth system dynamics*, 14(1), pp. 55–79.

Chen, Y., Liu, A. and Moore, J.C. (2020) 'Mitigation of Arctic permafrost carbon loss through stratospheric aerosol geoengineering', *Nature communications*, 11(1), p. 2430.

Cherry, T.L. *et al.* (2023) 'Climate cooperation in the shadow of solar geoengineering: an experimental investigation of the moral hazard conjecture', *Environmental politics*, 32(2), pp. 362–370.

Comyn-Platt, E. *et al.* (2018) 'Carbon budgets for 1.5 and 2 °C targets lowered by natural wetland and permafrost feedbacks', *Nature geoscience*, 11(8), pp. 568–573.

Costa, D.F. *et al.* (2022) 'The most extreme heat waves in Amazonia happened under extreme dryness', *Climate Dynamics*, 59(1), pp. 281–295.

Couce, E. *et al.* (2013) 'Tropical coral reef habitat in a geoengineered, high-CO2world', *Geophysical research letters*, 40(9), pp. 1799–1805.

DeConto, R.M. *et al.* (2021) 'The Paris Climate Agreement and future sea-level rise from Antarctica', *Nature*, 593(7857), pp. 83–89.

DeConto, R.M. and Pollard, D. (2016) 'Contribution of Antarctica to past and future sea-level rise',

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Nature, 531(7596), pp. 591–597.

Delworth, T.L. and Zeng, F. (2016) 'The Impact of the North Atlantic Oscillation on Climate through Its Influence on the Atlantic Meridional Overturning Circulation', *Journal of climate*, 29(3), pp. 941–962.

Dias, F.B. *et al.* (2021) 'Subpolar Southern Ocean Response to Changes in the Surface Momentum, Heat, and Freshwater Fluxes under 2xCO2', *Journal of climate*, 34(21), pp. 8755–8775.

Ditlevsen, P.D. and Johnsen, S.J. (2010) 'Tipping points: Early warning and wishful thinking', *Geophysical research letters*, 37(19). Available at: https://doi.org/10.1029/2010gl044486.

~~Douglas, T.A., Turetsky, M.R. and Koven, C.D. (2020) 'Increased rainfall stimulates permafrost thaw across a variety of Interior Alaskan boreal ecosystems', *npj Climate and Atmospheric Science*, 3(1), pp. 1–7.~~

~~Duffey, A. *et al.* (2023) 'Solar geoengineering in the polar regions: A review', *Earth's future*, 11(6). Available at: https://doi.org/10.1029/2023ef003679.~~

~~Edwards, T.L. *et al.* (2021) 'Projected land ice contributions to twenty-first-century sea level rise', *Nature*, 593(7857), pp. 74–82.~~

~~Enderlin, E.M. *et al.* (2014) 'An improved mass budget for the Greenland ice sheet', *Geophysical research letters*, 41(3), pp. 866–872.~~

~~Fan, Y. *et al.* (2021) 'Solar geoengineering can alleviate climate change pressures on crop yields', *Nature food*, 2(5), pp. 373–381.~~

~~Fasullo, J.T. *et al.* (2018) 'Persistent polar ocean warming in a strategically geoengineered climate', *Nature geoscience*, 11(12), pp. 910–914.~~

~~Fasullo, J.T. and Richter, J.H. (2023) 'Dependence of strategic solar climate intervention on background scenario and model physics', *Atmospheric Chemistry and Physics*, 23(1), pp. 163–182.~~

~~Favier, L. *et al.* (2014) 'Retreat of Pine Island Glacier controlled by marine ice-sheet instability', *Nature climate change*, 4(2), pp. 117–121.~~

~~Fetterer, F.;. K.K.;. M.W.;. S.M.;. W.A. (2017) 'Sea Ice Index, Version 3'. NSIDC. Available at: https://doi.org/~~Dotto, T.S. *et al.* (2019) 'Wind-Driven Processes Controlling Oceanic Heat Delivery to the Amundsen Sea, Antarctica', *Journal of physical oceanography*, 49(11), pp. 2829–2849.

Douglas, T.A., Turetsky, M.R. and Koven, C.D. (2020) 'Increased rainfall stimulates permafrost thaw across a variety of Interior Alaskan boreal ecosystems', *npj Climate and Atmospheric Science*, 3(1), pp. 1–7.

Duffey, A. *et al.* (2023) 'Solar geoengineering in the polar regions: A review', *Earth's future*, 11(6). Available at: https://doi.org/10.1029/2023ef003679.

Durand, M. *et al.* (2021) 'Diffuse solar radiation and canopy photosynthesis in a changing

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

environment', *Agricultural and Forest Meteorology*, 311, p. 108684.

Edwards, T.L. *et al.* (2019) 'Revisiting Antarctic ice loss due to marine ice-cliff instability', *Nature*, 566(7742), pp. 58–64.

Edwards, T.L. *et al.* (2021) 'Projected land ice contributions to twenty-first-century sea level rise', *Nature*, 593(7857), pp. 74–82.

Enderlin, E.M. *et al.* (2014) 'An improved mass budget for the Greenland ice sheet', *Geophysical research letters*, 41(3), pp. 866–872.

Fan, Y. *et al.* (2021) 'Solar geoengineering can alleviate climate change pressures on crop yields', *Nature food*, 2(5), pp. 373–381.

Fasullo, J.T. *et al.* (2018) 'Persistent polar ocean warming in a strategically geoengineered climate', *Nature geoscience*, 11(12), pp. 910–914.

Fasullo, J.T. and Richter, J.H. (2023) 'Dependence of strategic solar climate intervention on background scenario and model physics', *Atmospheric Chemistry and Physics*, 23(1), pp. 163–182.

Fetterer, F.;. K.K.;. M.W.;. S.M.;. W.A. (2017) 'Sea Ice Index, Version 3'. NSIDC. Available at: https://doi.org/10.7265/N5K072F8.

Fettweis, X. *et al.* (2021) 'Brief communication: Reduction in the future Greenland ice sheet surface melt with the help of solar geoengineering', *The cryosphere*, 15(6), pp. 3013–3019.

Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu (2021) 'Ocean, Cryosphere and Sea Level Change', in *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 1211–1362.

Fretwell, P. *et al.* (2013) 'Bedmap2: improved ice bed, surface and thickness datasets for Antarctica', *The cryosphere*, 7(1), pp. 375–393.

Fuss, S. *et al.* (2018) 'Negative emissions—Part 2: Costs, potentials and side effects', *Environmental research letters: ERL [Web site]*, 13(6), p. 063002.

Garbe, J. *et al.* (2020) 'The hysteresis of the Antarctic Ice Sheet', *Nature*, 585(7826), pp. 538–544.

Gardner, T.A. *et al.* (2005) 'Hurricanes and Caribbean coral reefs: Impacts, recovery patterns, and role in long-term decline', *Ecology*, 86(1), pp. 174–184.

Gasser, T. *et al.* (2018) 'Path-dependent reductions in CO2 emission budgets caused by permafrost carbon release', *Nature geoscience*, 11(11), pp. 830–835.

Gent, P.R. (2018) 'A commentary on the Atlantic meridional overturning circulation stability in climate models', *Ocean Modelling*, 122, pp. 57–66.

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Goddard, P.B. *et al.* (2023) ‘The impacts of Stratospheric Aerosol Injection on Antarctic ice loss depend on injection location’. Available at: Fettweis, X. *et al.* (2021) ‘Brief communication: Reduction in the future Greenland ice sheet surface melt with the help of solar geoengineering’, *The cryosphere*, 15(6), pp. 3013–3019.

Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu (2021) ‘Ocean, Cryosphere and Sea Level Change’, in *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 1211–1362.

Garbe, J. *et al.* (2020) ‘The hysteresis of the Antarctic Ice Sheet’, *Nature*, 585(7826), pp. 538–544.

Gardner, T.A. *et al.* (2005) ‘Hurricanes and Caribbean coral reefs: Impacts, recovery patterns, and role in long-term decline’, *Ecology*, 86(1), pp. 174–184.

Gasser, T. *et al.* (2018) ‘Path-dependent reductions in CO2 emission budgets caused by permafrost carbon release’, *Nature geoscience*, 11(11), pp. 830–835.

Gent, P.R. (2018) ‘A commentary on the Atlantic meridional overturning circulation stability in climate models’, *Ocean Modelling*, 122, pp. 57–66.

Goddard, P.B. *et al.* (2023) ‘The impacts of Stratospheric Aerosol Injection on Antarctic ice loss depend on injection location’. Available at: https://www.authorea.com/doi/full/10.22541/essoar.168677217.72510223.

Goelzer, H. *et al.* (2020) ‘The future sea-level contribution of the Greenland ice sheet: a multi-model ensemble study of ISMIP6’, *The cryosphere*, 14(9), pp. 3071–3096.

Golledge, N.R. *et al.* (2015) ‘The multi-millennial Antarctic commitment to future sea-level rise’, *Nature*, 526(7573), pp. 421–425.

Golledge, N.R. *et al.* (2019) ‘Global environmental consequences of twenty-first-century ice-sheet melt’, *Nature*, 566(7742), pp. 65–72.

Gregory, J.M. *et al.* (2016) ‘The Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP) contribution to CMIP6: investigation of sea-level and ocean climate change in response to CO_2 forcing’, *Geoscientific model development*, 9(11), pp. 3993–4017.

Gregory, J.M., George, S.E. and Smith, R.S. (2020) ‘Large and irreversible future decline of the Greenland ice sheet’, *The cryosphere*, 14(12), pp. 4299–4322.

Grosse, G. *et al.* (2011) ‘Vulnerability of high-latitude soil organic carbon in North America to disturbance’, *Journal of geophysical research*, 116(G00K06). Available at: https://doi.org/10.1029/2010jg001507.

Grossiord, C. *et al.* (2020) ‘Plant responses to rising vapor pressure deficit’, *The New phytologist*,

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

226(6), pp. 1550–1566.

Gudmundsson, G.H. (2013) 'Ice-shelf buttressing and the stability of marine ice sheets', *The cryosphere*, 7(2), pp. 647–655.

Heutel, G., Moreno-Cruz, J. and Shayegh, S. (2016) 'Climate tipping points and solar geoengineering', *Journal of economic behavior & organization*, 132, pp. 19–45.

Heyward, C. and Rayner, S. (2016) 'Apocalypse nicked! Stolen rhetoric in early geoengineering advocacy', *Anthropology and Climate Change: From Actions to Transformations*, pp. 86–104.

Hezel P. J., Zhang X., Bitz C. M., Kelly B. P., Massonnet F. (2012) 'Projected decline in spring snow depth on Arctic sea ice caused by progressively later autumn open ocean freeze-up this century', *Geophysical research letters* [Preprint]. Available at: https://doi.org/10.1029/2012GL052794.

Hock, R. *et al.* (2019) 'GlacierMIP – A model intercomparison of global-scale glacier mass-balance models and projections', *Journal of Glaciology*, 65(251), pp. 453–467.

Hoegh-Guldberg, O. *et al.* (2007) 'Coral reefs under rapid climate change and ocean acidification', *Science*, 318(5857), pp. 1737–1742.

Holbrook, S.J. *et al.* (2016) 'Coral Reef Resilience, Tipping Points and the Strength of Herbivory', *Scientific reports*, 6, p. 35817.

Holling, C.S. (1973) 'Resilience and Stability of Ecological Systems', *Annual review of ecology and systematics*, 4(1), pp. 1–23.

Horton, J.B. (2015) 'The emergency framing of solar geoengineering: Time for a different approach', *The Anthropocene Review*, 2(2), pp. 147–151.

Horton, J. and Keith, D. (2016) 'Solar geoengineering and obligations to the global poor', *Climate justice and geoengineering: Ethics and policy in the atmospheric Anthropocene*, pp. 79–92.

Hughes, T.P. *et al.* (2017) 'Global warming and recurrent mass bleaching of corals', *Nature*, 543(7645), pp. 373–377.

Hugonnet, R. *et al.* (2021) 'Accelerated global glacier mass loss in the early twenty-first century', *Nature*, 592(7856), pp. 726–731.

IMBIE Team (2020) 'Mass balance of the Greenland Ice Sheet from 1992 to 2018', *Nature*, 579(7798), pp. 233–239.

Intergovernmental Panel on Climate Change (IPCC) (2023) *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Irvine, P. *et al.* (2019) 'Halving warming with idealized solar geoengineering moderates key climate hazards', *Nature climate change*, 9(4), pp. 295–299.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Irvine, P.J. *et al.* (2009) 'The fate of the Greenland Ice Sheet in a geoengineered, high CO2 world', *Environmental research letters: ERL [Web site]*, 4(4), p. 045109.

Irvine, P.J. (2012) *Climatic effects of solar radiation management geoengineering*. University of Bristol. Available at: Goelles, T., Bøggild, C. and Greve, R. (2015) 'Ice sheet mass loss caused by dust and black carbon accumulation', *The Cryosphere*, 9, pp. 1845–1856.

Goelzer, H. *et al.* (2020) 'The future sea-level contribution of the Greenland ice sheet: a multi-model ensemble study of ISMIP6', *The cryosphere*, 14(9), pp. 3071–3096.

Golledge, N.R. *et al.* (2015) 'The multi-millennial Antarctic commitment to future sea-level rise', *Nature*, 526(7573), pp. 421–425.

Golledge, N.R. *et al.* (2019) 'Global environmental consequences of twenty-first-century ice-sheet melt', *Nature*, 566(7742), pp. 65–72.

Goyal, R. *et al.* (2021) 'Historical and projected changes in the southern hemisphere surface westerlies', *Geophysical research letters*, 48(4). Available at: https://doi.org/10.1029/2020gl090849.

Gregory, J.M. *et al.* (2016) 'The Flux-Anomaly-Forced Model Intercomparison Project (FAFMIP) contribution to CMIP6: investigation of sea-level and ocean climate change in response to CO_2 forcing', *Geoscientific model development*, 9(11), pp. 3993–4017.

Grosse, G. *et al.* (2011) 'Vulnerability of high-latitude soil organic carbon in North America to disturbance', *Journal of geophysical research*, 116(G00K06). Available at: https://doi.org/10.1029/2010jg001507.

Grossiord, C. *et al.* (2020) 'Plant responses to rising vapor pressure deficit', *The New phytologist*, 226(6), pp. 1550–1566.

Gudmundsson, G.H. (2013) 'Ice-shelf buttressing and the stability of marine ice sheets', *The cryosphere*, 7(2), pp. 647–655.

Gudmundsson, G.H. *et al.* (2019) 'Instantaneous Antarctic ice sheet mass loss driven by thinning ice shelves', *Geophysical research letters*, 46(23), pp. 13903–13909.

Hankel, C. and Tziperman, E. (2021) 'The Role of Atmospheric Feedbacks in Abrupt Winter Arctic Sea Ice Loss in Future Warming Scenarios', *Journal of climate*, 34(11), pp. 4435–4447.

Hassan, T. *et al.* (2021) 'Anthropogenic aerosol forcing of the Atlantic meridional overturning circulation and the associated mechanisms in CMIP6 models', *Atmospheric Chemistry and Physics*, 21(8), pp. 5821–5846.

Heutel, G., Moreno-Cruz, J. and Shayegh, S. (2016) 'Climate tipping points and solar geoengineering', *Journal of economic behavior & organization*, 132, pp. 19–45.

Hezel P. J., Zhang X., Bitz C. M., Kelly B. P., Massonnet F. (2012) 'Projected decline in spring snow depth on Arctic sea ice caused by progressively later autumn open ocean freeze-up this century',

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Geophysical research letters [Preprint]. Available at: https://doi.org/10.1029/2012GL052794.

Hock, R. *et al.* (2019) 'GlacierMIP – A model intercomparison of global-scale glacier mass-balance models and projections', *Journal of Glaciology*, 65(251), pp. 453–467.

Hoegh-Guldberg, O. *et al.* (2007) 'Coral reefs under rapid climate change and ocean acidification', *Science*, 318(5857), pp. 1737–1742.

Holbrook, S.J. *et al.* (2016) 'Coral Reef Resilience, Tipping Points and the Strength of Herbivory', *Scientific reports*, 6, p. 35817.

Holland, P.R. *et al.* (2019) 'West Antarctic ice loss influenced by internal climate variability and anthropogenic forcing', *Nature geoscience*, 12(9), pp. 718–724.

Horton, J. and Keith, D. (2016) 'Solar geoengineering and obligations to the global poor', *Climate justice and geoengineering: Ethics and policy in the atmospheric Anthropocene*, pp. 79–92.

Hughes, T.P. *et al.* (2017) 'Global warming and recurrent mass bleaching of corals', *Nature*, 543(7645), pp. 373–377.

Hugonnet, R. *et al.* (2021) 'Accelerated global glacier mass loss in the early twenty-first century', *Nature*, 592(7856), pp. 726–731.

IMBIE Team (2020) 'Mass balance of the Greenland Ice Sheet from 1992 to 2018', *Nature*, 579(7798), pp. 233–239.

Im, E.-S., Pal, J.S. and Eltahir, E.A.B. (2017) 'Deadly heat waves projected in the densely populated agricultural regions of South Asia', *Science advances*, 3(8), p. e1603322.

Intergovernmental Panel on Climate Change (IPCC) (2023) *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Irvine, P.J. *et al.* (2019) 'Halving warming with idealized solar geoengineering moderates key climate hazards', *Nature climate change*, 9(4), pp. 295–299.

Irvine, P.J. *et al.* (2009) 'The fate of the Greenland Ice Sheet in a geoengineered, high CO2 world', *Environmental research letters: ERL [Web site]*, 4(4), p. 045109.

Irvine, P.J. (2012) *Climatic effects of solar radiation management geoengineering*. University of Bristol. Available at: https://ethos.bl.uk/OrderDetails.do?uin=uk.bl.ethos.573384 (Accessed: 17 July 2023).

~~Irvine, P.J., Keith, D.W. and Moore, J. (2018) 'Brief communication: Understanding solar geoengineering's potential to limit sea level rise requires attention from cryosphere experts', *The cryosphere*, 12(7), pp. 2501–2513.~~

~~Ito, A. (2017) 'Solar radiation management and ecosystem functional responses', *Climatic change*, 142(1), pp. 53–66.~~

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Jackson, L.C. *et al.* (2022) 'Understanding AMOC stability: the North Atlantic hosing model intercomparison project', *Geoscientific Model Development Discussions*, 2022, pp. 1–32.

Jacobs, S.S. *et al.* (2011) 'Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf', *Nature geoscience*, 4(8), pp. 519–523.

Jiang, J. *et al.* (2019) 'Stratospheric sulfate aerosol geoengineering could alter the high-latitude seasonal cycle', *Geophysical research letters*, 46(23), pp. 14153–14163.

Jiménez-Muñoz, J.C. *et al.* (2016) 'Record-breaking warming and extreme drought in the Amazon rainforest during the course of El Niño 2015-2016', *Scientific reports*, 6, p. 33130.

Jin, X., Cao, L. and Zhang, J. (2022) 'Effects of solar radiation modification on the ocean carbon cycle: An earth system modeling study', *Atmospheric and Oceanic Science Letters*, 15(3), p. 100187.

Johnson, E. and Rupper, S. (2020) 'An examination of physical processes that trigger the albedo-feedback on glacier surfaces and implications for regional glacier mass balance across high mountain Asia', *Frontiers of earth science*, 8. Available at: https://doi.org/Irvine, P.J., Keith, D.W. and Moore, J. (2018) 'Brief communication: Understanding solar geoengineering's potential to limit sea level rise requires attention from cryosphere experts', *The cryosphere*, 12(7), pp. 2501–2513.

Ito, A. (2017) 'Solar radiation management and ecosystem functional responses', *Climatic change*, 142(1), pp. 53–66.

Jackson, L.C. *et al.* (2023) 'Understanding AMOC stability: the North Atlantic hosing model intercomparison project', *Geoscientific Model Development Discussions*, 2022, pp. 1–32.

Jacobs, S.S. *et al.* (2011) 'Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf', *Nature geoscience*, 4(8), pp. 519–523.

Jiang, J. *et al.* (2019) 'Stratospheric sulfate aerosol geoengineering could alter the high-latitude seasonal cycle', *Geophysical research letters*, 46(23), pp. 14153–14163.

Jiang, J., Hastings, A. and Lai, Y.-C. (2019) 'Harnessing tipping points in complex ecological networks', *Journal of the Royal Society, Interface / the Royal Society*, 16(158), p. 20190345.

Jiménez-Muñoz, J.C. *et al.* (2016) 'Record-breaking warming and extreme drought in the Amazon rainforest during the course of El Niño 2015-2016', *Scientific reports*, 6, p. 33130.

Jin, X., Cao, L. and Zhang, J. (2022) 'Effects of solar radiation modification on the ocean carbon cycle: An earth system modeling study', *Atmospheric and Oceanic Science Letters*, 15(3), p. 100187.

Johnson, E. and Rupper, S. (2020) 'An examination of physical processes that trigger the albedo-feedback on glacier surfaces and implications for regional glacier mass balance across high mountain Asia', *Frontiers of earth science*, 8. Available at: https://doi.org/10.3389/feart.2020.00129.

Johnson, G.C. and Lyman, J.M. (2020) 'Warming trends increasingly dominate global ocean', *Nature climate change*, 10(8), pp. 757–761.

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Johnson, H.L. *et al.* (2019) 'Recent contributions of theory to our understanding of the Atlantic meridional overturning circulation', *Journal of Geophysical Research, C: Oceans*, 124(8), pp. 5376–5399.

Jones, A.C. *et al.* (2017) 'Impacts of hemispheric solar geoengineering on tropical cyclone frequency', *Nature communications*, 8(1), pp. 1–10.

Jones, A. C., Hawcroft, M. K., Haywood, J. M., Jones, A., Guo, X., & Moore, J. C (2018) 'Regional climate impacts of stabilizing global warming at 1.5 K using solar geoengineering', *Earth's Future* [Preprint]. Available at: https://doi.org/10.1002/2017EF000720.

Jouffray, J.-B. *et al.* (2019) 'Parsing human and biophysical drivers of coral reef regimes', *Proceedings. Biological sciences / The Royal Society*, 286(1896), p. 20182544.

Joughin, I., Smith, B.E. and Medley, B. (2014) 'Marine ice sheet collapse potentially under way for the Thwaites Glacier Basin, West Antarctica', *Science*, 344(6185), pp. 735–738.

Katsman, C.A. *et al.* (2018) 'Sinking of dense north Atlantic waters in a global ocean model: Location and controls', *Journal of Geophysical Research, C: Oceans*, 123(5), pp. 3563–3576.

Keith, D.W. *et al.* (2016) 'Stratospheric solar geoengineering without ozone loss', *Proceedings of the National Academy of Sciences of the United States of America*, 113(52), pp. 14910–14914.

Klein, S.A. and Hartmann, D.L. (1993) 'The Seasonal Cycle of Low Stratiform Clouds', *Journal of climate*, 6(8), pp. 1587–1606.

Kravitz, B. *et al.* (2011) 'The geoengineering model intercomparison project (GeoMIP)', *Atmospheric Science Letters*, 12(2), pp. 162–167.

Kravitz, B. *et al.* (2013) 'Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP)', *Journal of geophysical research*, 118(15), pp. 8320–8332.

Kuswanto, H. *et al.* (2022) 'Impact of solar geoengineering on temperatures over the Indonesian Maritime Continent', *International Journal of Climatology*, 42(5), pp. 2795–2814.

Lago, V. and England, M.H. (2019) 'Projected slowdown of Antarctic Bottom Water formation in response to amplified meltwater contributions', *Journal of climate*, 32(19), pp. 6319–6335.

Lee, H. *et al.* (2019) 'The response of permafrost and high-latitude ecosystems under large-scale stratospheric aerosol injection and its termination', *Earth's future*, 7(6), pp. 605–614.

Lee, W. *et al.* (2020) 'Expanding the design space of stratospheric aerosol geoengineering to include precipitation-based objectives and explore trade-offs', *Earth system dynamics*, 11(4), pp. 1051–1072.

Lee, W.R. *et al.* (2021) 'High-latitude stratospheric aerosol geoengineering can be more effective if injection is limited to spring', *Geophysical research letters*, 48(9). Available at: https://doi.org/10.1029/2021gl092696.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Lee, W.R. *et al.* (2023) 'High-latitude stratospheric aerosol injection to preserve the arctic', *Earth's future*, 11(1). Available at: https://doi.org/10.1029/2022ef003052.

Legagneux, P. *et al.* (2018) 'Our house is burning: Discrepancy in climate change vs. Biodiversity coverage in the media as compared to scientific literature', *Frontiers in ecology and evolution*, 5. Available at: https://doi.org/10.3389/fevo.2017.00175.

Lenaerts, J.T.M. *et al.* (2019) 'Observing and Modeling Ice Sheet Surface Mass Balance', *Reviews of geophysics* , 57(2), pp. 376–420.

Lenton, T.M. *et al.* (2008) 'Tipping elements in the Earth's climate system', *Proceedings of the National Academy of Sciences of the United States of America*, 105(6), pp. 1786–1793.

Lenton, T.M. (2018) 'Can emergency geoengineering really prevent climate tipping points?', *Geoengineering Our Climate?* [Preprint]. Available at: https://doi.org/Johnson, H.L. *et al.* (2019) 'Recent contributions of theory to our understanding of the Atlantic meridional overturning circulation', *Journal of Geophysical Research, C: Oceans*, 124(8), pp. 5376–5399.

Jones, A.C. *et al.* (2017) 'Impacts of hemispheric solar geoengineering on tropical cyclone frequency', *Nature communications*, 8(1), pp. 1–10.

Jones, A. C., Hawcroft, M. K., Haywood, J. M., Jones, A., Guo, X., & Moore, J. C (2018) 'Regional climate impacts of stabilizing global warming at 1.5 K using solar geoengineering', *Earth's Future* [Preprint]. Available at: https://doi.org/10.1002/2017EF000720.

Jouffray, J.-B. *et al.* (2019) 'Parsing human and biophysical drivers of coral reef regimes', *Proceedings. Biological sciences / The Royal Society*, 286(1896), p. 20182544.

Kang, S. *et al.* (2020) 'A review of black carbon in snow and ice and its impact on the cryosphere', *Earth-Science Reviews*, 210, p. 103346.

Katsman, C.A. *et al.* (2018) 'Sinking of dense north Atlantic waters in a global ocean model: Location and controls', *Journal of Geophysical Research, C: Oceans*, 123(5), pp. 3563–3576.

Keith, D.W. *et al.* (2016) 'Stratospheric solar geoengineering without ozone loss', *Proceedings of the National Academy of Sciences of the United States of America*, 113(52), pp. 14910–14914.

Klein, S.A. and Hartmann, D.L. (1993) 'The Seasonal Cycle of Low Stratiform Clouds', *Journal of climate*, 6(8), pp. 1587–1606.

Kravitz, B. *et al.* (2011) 'The geoengineering model intercomparison project (GeoMIP)', *Atmospheric Science Letters*, 12(2), pp. 162–167.

Kravitz, B. *et al.* (2013) 'Climate model response from the Geoengineering Model Intercomparison Project (GeoMIP)', *Journal of geophysical research*, 118(15), pp. 8320–8332.

Kuswanto, H. *et al.* (2022) 'Impact of solar geoengineering on temperatures over the Indonesian Maritime Continent', *International Journal of Climatology*, 42(5), pp. 2795–2814.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Lago, V. and England, M.H. (2019) ‘Projected slowdown of Antarctic Bottom Water formation in response to amplified meltwater contributions’, *Journal of climate*, 32(19), pp. 6319–6335.

Lee, H. *et al.* (2019) ‘The response of permafrost and high-latitude ecosystems under large-scale stratospheric aerosol injection and its termination’, *Earth’s future*, 7(6), pp. 605–614.

Lee, W. *et al.* (2020) ‘Expanding the design space of stratospheric aerosol geoengineering to include precipitation-based objectives and explore trade-offs’, *Earth system dynamics*, 11(4), pp. 1051–1072.

Lee, W.R. *et al.* (2021) ‘High-latitude stratospheric aerosol geoengineering can be more effective if injection is limited to spring’, *Geophysical research letters*, 48(9). Available at: https://doi.org/10.1029/2021gl092696.

Lee, W.R. *et al.* (2023) ‘High-latitude stratospheric aerosol injection to preserve the arctic’, *Earth’s future*, 11(1). Available at: https://doi.org/10.1029/2022ef003052.

Legagneux, P. *et al.* (2018) ‘Our house is burning: Discrepancy in climate change vs. Biodiversity coverage in the media as compared to scientific literature’, *Frontiers in ecology and evolution*, 5. Available at: https://doi.org/10.3389/fevo.2017.00175.

Lenaerts, J.T.M. *et al.* (2019) ‘Observing and Modeling Ice Sheet Surface Mass Balance’, *Reviews of geophysics* , 57(2), pp. 376–420.

Lenton, T.M. *et al.* (2008) ‘Tipping elements in the Earth’s climate system’, *Proceedings of the National Academy of Sciences of the United States of America*, 105(6), pp. 1786–1793.

Lenton, T.M. (2018) ‘Can emergency geoengineering really prevent climate tipping points?’, *Geoengineering Our Climate?* [Preprint]. Available at: https://doi.org/10.4324/9780203485262-8/emergency-geoengineering-really-prevent-climate-tipping-points-timothy-lenton.

~~Lenton, T.M. *et al.* (2019) *Climate tipping points — too risky to bet against*, *Nature Publishing Group UK*. Available at: https://doi.org/~~Lenton, T.M. *et al.* (2019) *Climate tipping points — too risky to bet against*, *Nature Publishing Group UK*. Available at: https://doi.org/10.1038/d41586-019-03595-0~~.~~

~~Liang, J. *et al.* (2022) ‘Co-limitation towards lower latitudes shapes global forest diversity gradients’, *Nature ecology & evolution*, 6(10), pp. 1423–1437.~~

~~Lipscomb, W.H. *et al.* (2021) ‘ISMIP6-based projections of ocean-forced Antarctic Ice Sheet evolution using the Community Ice Sheet Model’, *The cryosphere*, 15(2), pp. 633–661.~~

~~Liu, A., Moore, J.C. and Chen, Y. (2023) ‘PInc-PanTher estimates of Arctic permafrost soil carbon under the GeoMIP G6solar and G6sulfur experiments’, *Earth System Dynamics*, 14(1), pp. 39–53.~~

~~Liu, W., Fedorov, A. and Sévellec, F. (2019) ‘The Mechanisms of the Atlantic Meridional Overturning Circulation Slowdown Induced by Arctic Sea Ice Decline’, *Journal of climate*, 32(4), pp. 977–996.~~

~~Lohmann, J. and Ditlevsen, P.D. (2021) ‘Risk of tipping the overturning circulation due to increasing rates of ice melt’, *Proceedings of the National Academy of Sciences of the United States of America*,~~

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

118(9). Available at: https://doi.org/.

Lenton, T.M. *et al.* (2023) 'Global Tipping Points Report', in T.M. Lenton et al. (eds) *Global Tipping Points Report*. *COP28*, Exeter, UK: University of Exeter. Available at: https://eprints.whiterose.ac.uk/206881/ (Accessed: 15 January 2024).

Levermann, A. *et al.* (2012) 'Potential climatic transitions with profound impact on Europe', *Climatic change*, 110(3), pp. 845–878.

Levermann, A. and Winkelmann, R. (2016) 'A simple equation for the melt elevation feedback of ice sheets', *The cryosphere*, 10(4), pp. 1799–1807.

Liang, J. *et al.* (2022) 'Co-limitation towards lower latitudes shapes global forest diversity gradients', *Nature ecology & evolution*, 6(10), pp. 1423–1437.

Lipscomb, W.H. *et al.* (2021) 'ISMIP6-based projections of ocean-forced Antarctic Ice Sheet evolution using the Community Ice Sheet Model', *The cryosphere*, 15(2), pp. 633–661.

Li, Q. *et al.* (2023) 'Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater', *Nature*, 615(7954), pp. 841–847.

Liu, A., Moore, J.C. and Chen, Y. (2023) 'PInc-PanTher estimates of Arctic permafrost soil carbon under the GeoMIP G6solar and G6sulfur experiments', *Earth System Dynamics*, 14(1), pp. 39–53.

Liu, W., Fedorov, A. and Sévellec, F. (2019) 'The Mechanisms of the Atlantic Meridional Overturning Circulation Slowdown Induced by Arctic Sea Ice Decline', *Journal of climate*, 32(4), pp. 977–996.

Li, W. *et al.* (2023) 'Reassessment of growth-climate relations indicates the potential for decline across Eurasian boreal larch forests', *Nature communications*, 14(1), p. 3358.

Lohmann, J. and Ditlevsen, P.D. (2021) 'Risk of tipping the overturning circulation due to increasing rates of ice melt', *Proceedings of the National Academy of Sciences of the United States of America*, 118(9). Available at: https://doi.org/10.1073/pnas.2017989118.

Luke, C.M. and Cox, P.M. (2011) 'Soil carbon and climate change: from the Jenkinson effect to the compost-bomb instability', *European journal of soil science*, 62(1), pp. 5–12.

Lynch-Stieglitz, J. (2017) 'The Atlantic Meridional Overturning Circulation and Abrupt Climate Change', *Annual review of marine science*, 9, pp. 83–104.

MacDougall, A.H. *et al.* (2015) 'Sensitivity of carbon budgets to permafrost carbon feedbacks and non-CO2 forcings', *Environmental research letters: ERL [Web site]*, 10(12), p. 125003.

MacMartin, D.G. *et al.* (2016) 'Geoengineering with stratospheric aerosols: What do we not know after a decade of research?', *Earth's future*, 4(11), pp. 543–548.

MacMartin, D.G. *et al.* (2022) 'Scenarios for modeling solar radiation modification', *Proceedings of the National Academy of Sciences of the United States of America*, 119(33), p. e2202230119.

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

MacMartin, D.G., Ricke, K.L. and Keith, D.W. (2018) 'Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target', *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, 376(2119). Available at: https://doi.org/10.1098/rsta.2016.0454.

Madan, G. *et al.* (2023) 'The weakening AMOC under extreme climate change'. Available at: https://doi.org/Loriani, S. *et al.* (2023) 'Tipping points in ocean and atmosphere circulations', *EGUsphere*. Available at: https://doi.org/10.5194/egusphere-2023-2589.

Luke, C.M. and Cox, P.M. (2011) 'Soil carbon and climate change: from the Jenkinson effect to the compost-bomb instability', *European journal of soil science*, 62(1), pp. 5–12.

Lynch-Stieglitz, J. (2017) 'The Atlantic Meridional Overturning Circulation and Abrupt Climate Change', *Annual review of marine science*, 9, pp. 83–104.

MacDougall, A.H. *et al.* (2015) 'Sensitivity of carbon budgets to permafrost carbon feedbacks and non-CO2 forcings', *Environmental research letters: ERL [Web site]*, 10(12), p. 125003.

MacMartin, D.G. *et al.* (2022) 'Scenarios for modeling solar radiation modification', *Proceedings of the National Academy of Sciences of the United States of America*, 119(33), p. e2202230119.

MacMartin, D.G., Ricke, K.L. and Keith, D.W. (2018) 'Solar geoengineering as part of an overall strategy for meeting the 1.5°C Paris target', *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, 376(2119). Available at: https://doi.org/10.1098/rsta.2016.0454.

Madan, G. *et al.* (2023) 'The weakening AMOC under extreme climate change'. Available at: https://doi.org/10.21203/rs.3.rs-2718787/v1.

Malhi, Y. *et al.* (2009) 'Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest', *Proceedings of the National Academy of Sciences of the United States of America*, 106(49), pp. 20610–20615.

Mallett, R.D.C. *et al.* (2021) 'Record winter winds in 2020/21 drove exceptional Arctic sea ice transport', *Communications Earth & Environment*, 2(1), pp. 1–6.

Mall, R.K. *et al.* (2022) 'Climate Changes over the Indian Subcontinent: Scenarios and Impacts', in N. Khare (ed.) *Science, Policies and Conflicts of Climate Change: An Indian Perspective*. Cham: Springer International Publishing, pp. 27–52.

Marshall, J. and Speer, K. (2012) 'Closure of the meridional overturning circulation through Southern Ocean upwelling', *Nature geoscience*, 5(3), pp. 171–180.

Marzeion, B. *et al.* (2018) 'Limited influence of climate change mitigation on short-term glacier mass loss', *Nature climate change*, 8(4), pp. 305–308.

Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R., Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.) (2021) *Climate Change 2021: The Physical Science Basis.*

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change : Summary for Policymakers. Cambridge University Press.

McCusker, K.E., Battisti, D.S. and Bitz, C.M. (2012) 'The Climate Response to Stratospheric Sulfate Injections and Implications for Addressing Climate Emergencies', *Journal of climate*, 25(9), pp. 3096–3116.

McCusker, K.E., Battisti, D.S. and Bitz, C.M. (2015) 'Inability of stratospheric sulfate aerosol injections to preserve the West Antarctic Ice Sheet', *Geophysical research letters*, 42(12), pp. 4989–4997.

McGuire, A.D. *et al.* (2018) 'Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change', *Proceedings of the National Academy of Sciences of the United States of America*, 115(15), pp. 3882–3887.

McLaren, D. (2016) 'Mitigation deterrence and the "moral hazard" of solar radiation management', *Earth's future*, 4(12), pp. 596–602.

Meehl, G.A. *et al.* (2016) 'Antarctic sea-ice expansion between 2000 and 2014 driven by tropical Pacific decadal climate variability', *Nature geoscience*, 9(8), pp. 590–595.

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard, and E.A.G. Schuur (2019) 'Polar Regions', in H.-O. Pörtner, D.C. Roberts, V. MassonDelmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.) (ed.) *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 203–320.

Merryfield, J., Holland, M., & Monahan, H. (2008) 'Multiple equilibria and abrupt transitions in Arctic summer sea ice extent', in C.M.B.A.L.--B.T. E. T. DeWeaver (ed.) *Arctic Sea Ice Decline: Observations, Projections, Mechanisms, and Implications*, pp. 151–174.

Mishra, V. *et al.* (2020) 'Moist heat stress extremes in India enhanced by irrigation', *Nature geoscience*, 13(11), pp. 722–728.

Mishra, V., Aadhar, S. and Mahto, S.S. (2021) 'Anthropogenic warming and intraseasonal summer monsoon variability amplify the risk of future flash droughts in India', *npj Climate and Atmospheric Science*, 4(1), pp. 1–10.

Mollica, N.R. *et al.* (2018) 'Ocean acidification affects coral growth by reducing skeletal density', *Proceedings of the National Academy of Sciences of the United States of America*, 115(8), pp. 1754–1759.

Moore, J.C. *et al.* (2015) 'Atlantic hurricane surge response to geoengineering', *Proceedings of the National Academy of Sciences of the United States of America*, 112(45), pp. 13794–13799.

Moore, J.C. *et al.* (2019) 'Greenland ice sheet response to stratospheric aerosol injection geoengineering', *Earth's future*, 7(12), pp. 1451–1463.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Moore, J.C., Jevrejeva, S. and Grinsted, A. (2010) ‘Efficacy of geoengineering to limit 21st century sea-level rise’, *Proceedings of the National Academy of Sciences of the United States of America*, 107(36), pp. 15699–15703.

Morlighem, M. *et al.* (2017) ‘BedMachine v3: Complete Bed Topography and Ocean Bathymetry Mapping of Greenland From Multibeam Echo Sounding Combined With Mass Conservation’, *Geophysical research letters*, 44(21), pp. 11051–11061.

Nalam, A., Bala, G. and Modak, A. (2018) ‘Effects of Arctic geoengineering on precipitation in the tropical monsoon regions’, *Climate Dynamics*, 50(9), pp. 3375–3395.

National Academies of Sciences and Medicine (2021) *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*. Washington, DC: The National Academies Press.

Nikonovas, T. *et al.* (2020) ‘Near-complete loss of fire-resistant primary tropical forest cover in Sumatra and Kalimantan’, *Communications Earth & Environment*, 1(1), pp. 1–8.

North, G.R. (1984) ‘The Small Ice Cap Instability in Diffusive Climate Models’, *Journal of the Atmospheric Sciences*, 41(23), pp. 3390–3395.

Notz, D. (2009) ‘The future of ice sheets and sea ice: between reversible retreat and unstoppable loss’, *Proceedings of the National Academy of Sciences of the United States of America*, 106(49), pp. 20590–20595.

Notz,D. & Marotzke,J. (no date) ‘Observations reveal external driver for Arctic sea-ice retreat’, *Geophysical Research Letters* [Preprint]. Available at: https://doi.org/Malhi, Y. *et al.* (2009) ‘Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest’, *Proceedings of the National Academy of Sciences of the United States of America*, 106(49), pp. 20610–20615.

Mallett, R.D.C. *et al.* (2021) ‘Record winter winds in 2020/21 drove exceptional Arctic sea ice transport’, *Communications Earth & Environment*, 2(1), pp. 1–6.

Mall, R.K. *et al.* (2022) ‘Climate Changes over the Indian Subcontinent: Scenarios and Impacts’, in N. Khare (ed.) *Science, Policies and Conflicts of Climate Change: An Indian Perspective*. Cham: Springer International Publishing, pp. 27–52.

Marshall, J. and Speer, K. (2012) ‘Closure of the meridional overturning circulation through Southern Ocean upwelling’, *Nature geoscience*, 5(3), pp. 171–180.

Marzeion, B. *et al.* (2018) ‘Limited influence of climate change mitigation on short-term glacier mass loss’, *Nature climate change*, 8(4), pp. 305–308.

Marzeion, B. *et al.* (2020) ‘Partitioning the uncertainty of ensemble projections of global glacier mass change’, *Earth’s future*, 8(7). Available at: https://doi.org/10.1029/2019ef001470.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R., Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.) (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change : Summary for Policymakers*. Cambridge University Press.

Maurer, J.M. *et al.* (2019) 'Acceleration of ice loss across the Himalayas over the past 40 years', *Science advances*, 5(6), p. eaav7266.

McCusker, K.E., Battisti, D.S. and Bitz, C.M. (2012) 'The Climate Response to Stratospheric Sulfate Injections and Implications for Addressing Climate Emergencies', *Journal of climate*, 25(9), pp. 3096–3116.

McCusker, K.E., Battisti, D.S. and Bitz, C.M. (2015) 'Inability of stratospheric sulfate aerosol injections to preserve the West Antarctic Ice Sheet', *Geophysical research letters*, 42(12), pp. 4989–4997.

McLaren, D. (2016) 'Mitigation deterrence and the "moral hazard" of solar radiation management', *Earth's future*, 4(12), pp. 596–602.

Meehl, G.A. *et al.* (2016) 'Antarctic sea-ice expansion between 2000 and 2014 driven by tropical Pacific decadal climate variability', *Nature geoscience*, 9(8), pp. 590–595.

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard, and E.A.G. Schuur (2019) 'Polar Regions', in H.-O. Pörtner, D.C. Roberts, V. MassonDelmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.) (ed.) *The Ocean and Cryosphere in a Changing Climate: Special Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp. 203–320.

Merryfield, J., Holland, M., & Monahan, H. (2008) 'Multiple equilibria and abrupt transitions in Arctic summer sea ice extent', in C.M.B.A.L.--B.T. E. T. DeWeaver (ed.) *Arctic Sea Ice Decline: Observations, Projections, Mechanisms, and Implications*, pp. 151–174.

Mishra, V., Aadhar, S. and Mahto, S.S. (2021) 'Anthropogenic warming and intraseasonal summer monsoon variability amplify the risk of future flash droughts in India', *npj Climate and Atmospheric Science*, 4(1), pp. 1–10.

Mollica, N.R. *et al.* (2018) 'Ocean acidification affects coral growth by reducing skeletal density', *Proceedings of the National Academy of Sciences of the United States of America*, 115(8), pp. 1754–1759.

Moore, J.C. *et al.* (2015) 'Atlantic hurricane surge response to geoengineering', *Proceedings of the National Academy of Sciences of the United States of America*, 112(45), pp. 13794–13799.

Moore, J.C. *et al.* (2019) 'Greenland ice sheet response to stratospheric aerosol injection geoengineering', *Earth's future*, 7(12), pp. 1451–1463.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Moore, J.C. *et al.* (2023) ‘Reduced ice loss from Greenland under stratospheric aerosol injection’, *Journal of geophysical research. Earth surface*, 128(11). Available at: https://doi.org/10.1029/2023jf007112.

Moore, J.C., Jevrejeva, S. and Grinsted, A. (2010) ‘Efficacy of geoengineering to limit 21st century sea-level rise’, *Proceedings of the National Academy of Sciences of the United States of America*, 107(36), pp. 15699–15703.

Morlighem, M. *et al.* (2019) ‘Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet’, *Nature geoscience*, 13(2), pp. 132–137.

Mudge, L. and Bruno, J.F. (2023) ‘Disturbance intensification is altering the trait composition of Caribbean reefs, locking them into a low functioning state’, *Scientific reports*, 13(1), p. 14022.

Nalam, A., Bala, G. and Modak, A. (2018) ‘Effects of Arctic geoengineering on precipitation in the tropical monsoon regions’, *Climate Dynamics*, 50(9), pp. 3375–3395.

National Academies of Sciences and Medicine (2021) *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance*. Washington, DC: The National Academies Press.

Negi, V.S. *et al.* (2022) ‘Review and synthesis of climate change studies in the Himalayan region’, *Environment, Development and Sustainability*, 24(9), pp. 10471–10502.

Nian, D. *et al.* (2023) ‘A potential collapse of the Atlantic Meridional Overturning Circulation may stabilise eastern Amazonian rainforests’, *Communications Earth & Environment*, 4(1), pp. 1–11.

North, G.R. (1984) ‘The Small Ice Cap Instability in Diffusive Climate Models’, *Journal of the Atmospheric Sciences*, 41(23), pp. 3390–3395.

Notz, D. (2009) ‘The future of ice sheets and sea ice: between reversible retreat and unstoppable loss’, *Proceedings of the National Academy of Sciences of the United States of America*, 106(49), pp. 20590–20595.

Notz,D. & Marotzke,J. (no date) ‘Observations reveal external driver for Arctic sea-ice retreat’, *Geophysical Research Letters* [Preprint]. Available at: https://doi.org/10.1029/2012GL051094.

~~Notz, D. and SIMIP Community (2020) ‘Arctic sea ice in CMIP6’, *Geophysical research letters*, 47(10). Available at: https://doi.org/~~Notz, D. and SIMIP Community (2020) ‘Arctic sea ice in CMIP6’, *Geophysical research letters*, 47(10). Available at: https://doi.org/10.1029/2019gl086749.

~~Notz, D. and Stroeve, J. (2016) ‘Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission’, *Science*, 354(6313), pp. 747–750.~~

~~Notz, D. and Stroeve, J. (2018) ‘The Trajectory Towards a Seasonally Ice-Free Arctic Ocean’, *Current climate change reports*, 4(4), pp. 407–416.~~

~~Nowicki, S.M.J. *et al.* (2016) ‘Ice Sheet Model Intercomparison Project (ISMIP6) contribution to~~

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

~~CMIP6', *Geoscientific model development*, 9(12), pp. 4521–4545.~~

~~Numata, S. *et al.* (2022) 'Impacts of climate change on reproductive phenology in tropical rainforests of Southeast Asia', *Communications biology*, 5(1), p. 311.~~

~~Parkinson, C.L. (2019) 'A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic', *Proceedings of the National Academy of Sciences of the United States of America*, 116(29), pp. 14414–14423.~~

~~Pattyn, F. (2018) 'The paradigm shift in Antarctic ice sheet modelling', *Nature communications*, 9(1), p. 2728.~~

~~Pattyn, F. and Morlighem, M. (2020) 'The uncertain future of the Antarctic Ice Sheet', *Science*, 367(6484), pp. 1331–1335.~~

~~Pauling, A.G., Bushuk, M. and Bitz, C.M. (2021) 'Robust inter-hemispheric asymmetry in the response to symmetric volcanic forcing in model large ensembles', *Geophysical research letters*, 48(9). Available at: https://doi.org/~~Notz, D. and Stroeve, J. (2016) 'Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission', *Science*, 354(6313), pp. 747–750.

Notz, D. and Stroeve, J. (2018) 'The Trajectory Towards a Seasonally Ice-Free Arctic Ocean', *Current climate change reports*, 4(4), pp. 407–416.

Nowicki, S.M.J. *et al.* (2016) 'Ice Sheet Model Intercomparison Project (ISMIP6) contribution to CMIP6', *Geoscientific model development*, 9(12), pp. 4521–4545.

Orihuela-Pinto, B., England, M.H. and Taschetto, A.S. (2022) 'Interbasin and interhemispheric impacts of a collapsed Atlantic Overturning Circulation', *Nature climate change*, 12(6), pp. 558–565.

Osmond, M.M. and Klausmeier, C.A. (2017) 'An evolutionary tipping point in a changing environment', *Evolution; international journal of organic evolution*, 71(12), pp. 2930–2941.

Otosaka, I.N. *et al.* (2023) 'Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020', *Earth System Science Data*, 15(4), pp. 1597–1616.

Pandit, M.K. *et al.* (2007) 'Unreported yet massive deforestation driving loss of endemic biodiversity in Indian Himalaya', *Biodiversity and conservation*, 16(1), pp. 153–163.

Parkinson, C.L. (2019) 'A 40-y record reveals gradual Antarctic sea ice increases followed by decreases at rates far exceeding the rates seen in the Arctic', *Proceedings of the National Academy of Sciences of the United States of America*, 116(29), pp. 14414–14423.

Pattyn, F. (2018) 'The paradigm shift in Antarctic ice sheet modelling', *Nature communications*, 9(1), p. 2728.

Pauling, A.G., Bushuk, M. and Bitz, C.M. (2021) 'Robust inter-hemispheric asymmetry in the response to symmetric volcanic forcing in model large ensembles', *Geophysical research letters*, 48(9). Available at: https://doi.org/10.1029/2021gl092558.

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

~~Pollard, D., DeConto, R.M. and Alley, R.B. (2015) ‘Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure’, *Earth and planetary science letters*, 412, pp. 112–121.~~

~~Potocki, M. *et al.* (2022) ‘Mt. Everest’s highest glacier is a sentinel for accelerating ice loss’, *npj Climate and Atmospheric Science*, 5(1), pp. 1–8.~~

~~Pritchard, H.D. *et al.* (2012) ‘Antarctic ice-sheet loss driven by basal melting of ice shelves’, *Nature*, 484(7395), pp. 502–505.~~

~~Raha, A. *et al.* (2012) ‘Climate change impacts on Indian Sunderbans: a time series analysis (1924–2008)’, *Biodiversity and conservation*, 21(5), pp. 1289–1307.~~

~~Rahmstorf, S. (1996) ‘On the freshwater forcing and transport of the Atlantic thermohaline circulation’, *Climate Dynamics*, 12(12), pp. 799–811.~~

~~Rahmstorf, S. (2006) ‘Thermohaline Ocean Circulation’, *Encyclopedia of Quaternary Sciences*. Available at:~~ Pettay, D.T. *et al.* (2015) ‘Microbial invasion of the Caribbean by an Indo-Pacific coral zooxanthella’, *Proceedings of the National Academy of Sciences of the United States of America*, 112(24), pp. 7513–7518.

Pflüger, D. *et al.* (2024) ‘Flawed emergency intervention: Slow ocean response to abrupt stratospheric aerosol injection’, *Geophysical research letters*, 51(5). Available at: https://doi.org/10.1029/2023gl106132.

Pollard, D., DeConto, R.M. and Alley, R.B. (2015) ‘Potential Antarctic Ice Sheet retreat driven by hydrofracturing and ice cliff failure’, *Earth and planetary science letters*, 412, pp. 112–121.

Potocki, M. *et al.* (2022) ‘Mt. Everest’s highest glacier is a sentinel for accelerating ice loss’, *npj Climate and Atmospheric Science*, 5(1), pp. 1–8.

Raha, A. *et al.* (2012) ‘Climate change impacts on Indian Sunderbans: a time series analysis (1924–2008)’, *Biodiversity and conservation*, 21(5), pp. 1289–1307.

Rahmstorf, S. (1996) ‘On the freshwater forcing and transport of the Atlantic thermohaline circulation’, *Climate Dynamics*, 12(12), pp. 799–811.

Rahmstorf, S. (2006) ‘Thermohaline Ocean Circulation’, *Encyclopedia of Quaternary Sciences*. Available at: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=002c63381346b970fbcf06c24a2e9cd800684ff9 (Accessed: 17 July 2023).

~~Rahmstorf, S. *et al.* (2015) ‘Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation’, *Nature climate change*, 5(5), pp. 475–480.~~

~~Ricke, K. *et al.* (2023) ‘Hydrological Consequences of Solar Geoengineering’, *Annual review of earth and planetary sciences*, 51(1), pp. 447–470.~~

~~Ricke, K. (2023) ‘Solar geoengineering is scary - that’s why we should research it’, *Nature*, 614(7948),~~

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

p. 391.

Ridley, J. *et al.* (2010) 'Thresholds for irreversible decline of the Greenland ice sheet', *Climate Dynamics*, 35(6), pp. 1049–1057.

Ridley, J.K. and Blockley, E.W. (2018) 'Brief communication: Solar radiation management not as effective as CO_2 mitigation for Arctic sea ice loss in hitting the 1.5 and 2 °C COP climate targets', *The cryosphere*, 12(10), pp. 3355–3360.

Ridley, J.K., Lowe, J.A. and Hewitt, H.T. (2012) 'How reversible is sea ice loss?', *The cryosphere*, 6(1), pp. 193–198.

Rietkerk, M. *et al.* (2021) 'Evasion of tipping in complex systems through spatial pattern formation', *Science*, 374(6564), p. eabj0359.

Rignot, E. *et al.* (2014) 'Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011', *Geophysical research letters*, 41(10), pp. 3502–3509.

Rignot, E. *et al.* (2019) 'Four decades of Antarctic Ice Sheet mass balance from 1979-2017', *Proceedings of the National Academy of Sciences of the United States of America*, 116(4), pp. 1095–1103.

Rind, D. *et al.* (2018) 'Multicentury instability of the Atlantic meridional circulation in rapid warming simulations with GISS ModelE2', *Journal of geophysical research*, 123(12), pp. 6331–6355.

Robinson, A., Calov, R. and Ganopolski, A. (2012) 'Multistability and critical thresholds of the Greenland ice sheet', *Nature climate change*, 2(6), pp. 429–432.

Rounce, D.R. *et al.* (2023) 'Global glacier change in the 21st century: Every increase in temperature matters', *Science*, 379(6627), pp. 78–83.

Ruiz-Pérez, G. and Vico, G. (2020) 'Effects of Temperature and Water Availability on Northern European Boreal Forests', *Frontiers in Forests and Global Change*, 3. Available at: https://doi.org/10.3389/ffgc.2020.00034.

Ruppel, C. and Kessler, J. (2016) 'The interaction of climate change and methane hydrates', *Reviews of Geophysics* [Preprint]. Available at: https://doi.org/Rao, M.P. *et al.* (2023) 'Approaching a thermal tipping point in the Eurasian boreal forest at its southern margin', *Communications Earth & Environment*, 4(1), pp. 1–10.

Ricke, K. *et al.* (2023) 'Hydrological Consequences of Solar Geoengineering', *Annual review of earth and planetary sciences*, 51(1), pp. 447–470.

Ricke, K. (2023) 'Solar geoengineering is scary - that's why we should research it', *Nature*, 614(7948), p. 391.

Ridley, J.K. and Blockley, E.W. (2018) 'Brief communication: Solar radiation management not as

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

effective as CO_2 mitigation for Arctic sea ice loss in hitting the 1.5 and 2 °C COP climate targets', *The cryosphere*, 12(10), pp. 3355–3360.

Ridley, J.K., Lowe, J.A. and Hewitt, H.T. (2012) 'How reversible is sea ice loss?', *The cryosphere*, 6(1), pp. 193–198.

Rietkerk, M. *et al.* (2021) 'Evasion of tipping in complex systems through spatial pattern formation', *Science*, 374(6564), p. eabj0359.

Rignot, E. *et al.* (2019) 'Four decades of Antarctic Ice Sheet mass balance from 1979-2017', *Proceedings of the National Academy of Sciences of the United States of America*, 116(4), pp. 1095–1103.

Rind, D. *et al.* (2018) 'Multicentury instability of the Atlantic meridional circulation in rapid warming simulations with GISS ModelE2', *Journal of geophysical research*, 123(12), pp. 6331–6355.

Ritchie, P.D.L. *et al.* (2021) 'Overshooting tipping point thresholds in a changing climate', *Nature*, 592(7855), pp. 517–523.

Roach, L.A. *et al.* (2020) 'Antarctic sea ice area in CMIP6', *Geophysical research letters*, 47(9). Available at: https://doi.org/10.1029/2019gl086729.

Robinson, A., Calov, R. and Ganopolski, A. (2012) 'Multistability and critical thresholds of the Greenland ice sheet', *Nature climate change*, 2(6), pp. 429–432.

Rounce, D.R. *et al.* (2023) 'Global glacier change in the 21st century: Every increase in temperature matters', *Science*, 379(6627), pp. 78–83.

Ruppel, C. and Kessler, J. (2016) 'The interaction of climate change and methane hydrates', *Reviews of Geophysics* [Preprint]. Available at: https://doi.org/10.1002/2016RG000534.

Salazar, A.M. and Tziperman, E. (2023) 'Exploring subtropical stratocumulus multiple equilibria using a mixed-layer model', *Journal of climate* [Preprint]. Available at: Salazar, A.M. and Tziperman, E. (2023) 'Exploring subtropical stratocumulus multiple equilibria using a mixed-layer model', *Journal of climate* [Preprint]. Available at: https://journals.ametsoc.org/view/journals/clim/36/8/JCLI-D-22-0528.1.xml.

Sasgen, I. *et al.* (2012) 'Timing and origin of recent regional ice-mass loss in Greenland', *Earth and planetary science letters*, 333-334, pp. 293–303.

Sayol, J.-M., Dijkstra, H. and Katsman, C. (2019) 'Seasonal and regional variations of sinking in the subpolar North Atlantic from a high-resolution ocean model', *Ocean Science*, 15(4), pp. 1033–1053.

Scambos, T., Hulbe, C. and Fahnestock, M. (2013) 'Climate-induced ice shelf disintegration in the antarctic peninsula', in *Antarctic Peninsula Climate Variability: Historical and Paleoenvironmental Perspectives*. Washington, D. C.: American Geophysical Union (Antarctic research series), pp. 79–92.

Schaefer, K., Lantuit, H., Romanovsky, V. E., Schuur, E. A. G., & Witt, R. (2014) 'The impact of the permafrost carbon feedback on global climate', *Environmental research letters: ERL [Web site]*, 9(8).

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Available at: https://doi.org/Sayol, J.-M., Dijkstra, H. and Katsman, C. (2019) 'Seasonal and regional variations of sinking in the subpolar North Atlantic from a high-resolution ocean model', *Ocean Science*, 15(4), pp. 1033–1053.

Schaefer, K., Lantuit, H., Romanovsky, V. E., Schuur, E. A. G., & Witt, R. (2014) 'The impact of the permafrost carbon feedback on global climate', *Environmental research letters: ERL [Web site]*, 9(8). Available at: https://doi.org/10.1088/1748-9326/9/8/085003.

Scheuchl, B. *et al.* (2016) 'Grounding line retreat of Pope, Smith, and Kohler Glaciers, West Antarctica, measured with Sentinel-1a radar interferometry data', *Geophysical research letters*, 43(16), pp. 8572–8579.

Schmitz, O.J. and Sylvén, M. (2023) 'Animating the Carbon Cycle: How Wildlife Conservation Can Be a Key to Mitigate Climate Change', *Environment: Science and Policy for Sustainable Development*, 65(3), pp. 5–17.

Schneider, T., Kaul, C.M. and Pressel, K.G. (2019) 'Possible climate transitions from breakup of stratocumulus decks under greenhouse warming', *Nature geoscience*, 12(3), pp. 163–167.

Schneider, T., Kaul, C.M. and Pressel, K.G. (2020) 'Solar geoengineering may not prevent strong warming from direct effects of CO_2 on stratocumulus cloud cover', *Proceedings of the National Academy of Sciences of the United States of America*, 117(48), pp. 30179–30185.

Schuur, E.A.G. *et al.* (2015) 'Climate change and the permafrost carbon feedback', *Nature*, 520(7546), pp. 171–179.

Schuur, E.A.G. *et al.* (2022) 'Permafrost and Climate Change: Carbon Cycle Feedbacks From the Warming Arctic', *Annual review of environment and resources*, 47(1), pp. 343–371.

Schwinger, J. *et al.* (2022) 'Emit now, mitigate later? Earth system reversibility under overshoots of different magnitudes and durations', *Earth System Dynamics*, 13(4), pp. 1641–1665.

Seidl, R. *et al.* (2017) 'Forest disturbances under climate change', *Nature climate change*, 7, pp. 395–402.

Serreze, M.C. *et al.* (2007) 'The large-scale energy budget of the Arctic', *Journal of geophysical research*, 112(D11). Available at: https://doi.org/10.1029/2006jd008230.

Serreze, M.C. *et al.* (2009) 'The emergence of surface-based Arctic amplification', *The cryosphere*, 3(1), pp. 11–19.

Serreze, M.C. and Barry, R.G. (2011) 'Processes and impacts of Arctic amplification: A research synthesis', *Global and planetary change*, 77(1), pp. 85–96.

Setty, S. *et al.* (2023) 'Loss of Earth system resilience during early Eocene transient global warming events', *Science advances*, 9(14), p. eade5466.

Sgubin, G. *et al.* (2017) 'Abrupt cooling over the North Atlantic in modern climate models', *Nature*

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Field Code Changed

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

communications, 8. Available at: https://doi.org/10.1038/ncomms14375.

Sharma, E. *et al.* (2009) *Biodiversity in the Himalayas – trends, perception and impacts of climate change*. Available at: Schmitt, R.J. *et al.* (2019) 'Experimental support for alternative attractors on coral reefs', *Proceedings of the National Academy of Sciences*, 116(10), pp. 4372–4381.

Schneider, T., Kaul, C.M. and Pressel, K.G. (2019) 'Possible climate transitions from breakup of stratocumulus decks under greenhouse warming', *Nature geoscience*, 12(3), pp. 163–167.

Schneider, T., Kaul, C.M. and Pressel, K.G. (2020) 'Solar geoengineering may not prevent strong warming from direct effects of CO_2 on stratocumulus cloud cover', *Proceedings of the National Academy of Sciences of the United States of America*, 117(48), pp. 30179–30185.

Schuur, E.A.G. *et al.* (2015) 'Climate change and the permafrost carbon feedback', *Nature*, 520(7546), pp. 171–179.

Schuur, E.A.G. *et al.* (2022) 'Permafrost and Climate Change: Carbon Cycle Feedbacks From the Warming Arctic', *Annual review of environment and resources*, 47(1), pp. 343–371.

Schwinger, J. *et al.* (2022) 'Emit now, mitigate later? Earth system reversibility under overshoots of different magnitudes and durations', *Earth System Dynamics*, 13(4), pp. 1641–1665.

Seidl, R. *et al.* (2017) 'Forest disturbances under climate change', *Nature climate change*, 7, pp. 395–402.

Serreze, M.C. *et al.* (2007) 'The large-scale energy budget of the Arctic', *Journal of geophysical research*, 112(D11). Available at: https://doi.org/10.1029/2006jd008230.

Serreze, M.C. *et al.* (2009) 'The emergence of surface-based Arctic amplification', *The cryosphere*, 3(1), pp. 11–19.

Serreze, M.C. and Barry, R.G. (2011) 'Processes and impacts of Arctic amplification: A research synthesis', *Global and planetary change*, 77(1), pp. 85–96.

Sgubin, G. *et al.* (2017) 'Abrupt cooling over the North Atlantic in modern climate models', *Nature communications*, 8. Available at: https://doi.org/10.1038/ncomms14375.

Shao, L. *et al.* (2020) 'The fertilization effect of global dimming on crop yields is not attributed to an improved light interception', *Global change biology*, 26(3), pp. 1697–1713.

Sharma, E. *et al.* (2009) *Biodiversity in the Himalayas – trends, perception and impacts of climate change*. Available at: http://www.indiaenvironmentportal.org.in/files/Biodiversity%20in%20the%20Himalayas.pdf (Accessed: 21 July 2023).

Shepherd, A. *et al.* (2012) 'A reconciled estimate of ice-sheet mass balance', *Science*, 338(6111), pp. 1183–1189.

Formatted: Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font color: Black

Field Code Changed

Formatted: Font color: Black

Formatted: No underline, Font color: Black

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Sievers, M. *et al.* (2020) 'Indian Sundarbans mangrove forest considered endangered under Red List of Ecosystems, but there is cause for optimism', *Biological conservation*, 251, p. 108751.

Simpson, I.R. *et al.* (2019) 'The regional hydroclimate response to stratospheric sulfate geoengineering and the role of stratospheric heating', *Journal of geophysical research*, 124(23), pp. 12587–12616.

Slater, A.G. and Lawrence, D.M. (2013) 'Diagnosing Present and Future Permafrost from Climate Models', *Journal of climate*, 26(15), pp. 5608–5623.

Smith, P. *et al.* (2019) 'Land-Management Options for Greenhouse Gas Removal and Their Impacts on Ecosystem Services and the Sustainable Development Goals', *Annual review of environment and resources*, 44(1), pp. 255–286.

Smith, W. *et al.* (2022) 'A subpolar-focused stratospheric aerosol injection deployment scenario', *Environmental Research Communications*, 4(9), p. 095009.

Smyth, J.E., Russotto, R.D. and Storelvmo, T. (2017) 'Thermodynamic and dynamic responses of the hydrological cycle to solar dimming', *Atmospheric Chemistry and Physics*, 17(10), pp. 6439–6453.

Stephens, J.C. *et al.* (2021) 'The risks of solar geoengineering research', *Science*, 372(6547), p. 1161.

Stokes, C.R. *et al.* (2022) 'Response of the East Antarctic Ice Sheet to past and future climate change', *Nature*, 608(7922), pp. 275–286.

Stommel, H. (1961) 'Thermohaline convection with two stable regimes of flow', *Tell'Us*, 13(2), pp. 224–230.

Strauss, J. *et al.* (2017) 'Deep Yedoma permafrost: A synthesis of depositional characteristics and carbon vulnerability', *Earth-Science Reviews*, 172, pp. 75–86.

Stroeve, J.C. *et al.* (2011) 'Sea ice response to an extreme negative phase of the Arctic Oscillation during winter 2009/2010', *Geophysical research letters*, 38(2). Available at: https://doi.org/Shepherd, A. *et al.* (2012) 'A reconciled estimate of ice-sheet mass balance', *Science*, 338(6111), pp. 1183–1189.

Sievers, M. *et al.* (2020) 'Indian Sundarbans mangrove forest considered endangered under Red List of Ecosystems, but there is cause for optimism', *Biological conservation*, 251, p. 108751.

Simpson, I.R. *et al.* (2019) 'The regional hydroclimate response to stratospheric sulfate geoengineering and the role of stratospheric heating', *Journal of geophysical research*, 124(23), pp. 12587–12616.

Slater, A.G. and Lawrence, D.M. (2013) 'Diagnosing Present and Future Permafrost from Climate Models', *Journal of climate*, 26(15), pp. 5608–5623.

Smith, W. *et al.* (2022) 'A subpolar-focused stratospheric aerosol injection deployment scenario', *Environmental Research Communications*, 4(9), p. 095009.

Smyth, J.E., Russotto, R.D. and Storelvmo, T. (2017) 'Thermodynamic and dynamic responses of the hydrological cycle to solar dimming', *Atmospheric Chemistry and Physics*, 17(10), pp. 6439–6453.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Staal, A. *et al.* (2020) 'Hysteresis of tropical forests in the 21st century', *Nature communications*, 11(1), p. 4978.

Stephens, J.C. *et al.* (2021) 'The risks of solar geoengineering research', *Science*, 372(6547), p. 1161.

Stokes, C.R. *et al.* (2022) 'Response of the East Antarctic Ice Sheet to past and future climate change', *Nature*, 608(7922), pp. 275–286.

Stommel, H. (1961) 'Thermohaline convection with two stable regimes of flow', *Tell'Us*, 13(2), pp. 224–230.

Strauss, J. *et al.* (2017) 'Deep Yedoma permafrost: A synthesis of depositional characteristics and carbon vulnerability', *Earth-Science Reviews*, 172, pp. 75–86.

Stroeve, J.C. *et al.* (2011) 'Sea ice response to an extreme negative phase of the Arctic Oscillation during winter 2009/2010', *Geophysical research letters*, 38(2). Available at: https://doi.org/10.1029/2010gl045662.

Stroeve, J. and Notz, D. (2015) 'Insights on past and future sea-ice evolution from combining observations and models', *Global and planetary change*, 135, pp. 119–132.

Surprise, K. (2020) 'Geopolitical ecology of solar geoengineering: from a "logic of multilateralism" to logics of militarization', *Journal of Political Ecology*, 27(1), pp. 213–235.

Swapna, P. *et al.* (2017) 'Multidecadal weakening of Indian summer monsoon circulation induces an increasing northern Indian ocean sea level', *Geophysical research letters*, 44(20), pp. 10,560–10,572.

Swingedouw, D. *et al.* (2021) 'On the risk of abrupt changes in the North Atlantic subpolar gyre in CMIP6 models', *Annals of the New York Academy of Sciences*, 1504(1), pp. 187–201.

Táíwò, O.O. and Talati, S. (2022) 'Who are the engineers? Solar geoengineering research and justice', *Global environmental politics*, 22(1), pp. 12–18.

Tan, M.L. *et al.* (2023) 'Impacts of Solar Radiation Management on Hydro-Climatic Extremes in Southeast Asia', *WATER*, 15(6), p. 1089.

Tedesco, M. *et al.* (2016) 'The darkening of the Greenland ice sheet: trends, drivers, and projections (1981–2100)', *The cryosphere*, 10(2), pp. 477–496.

Thoma, M., Jenkins, A. and Holland, D. (2008) 'Modelling circumpolar deep water intrusions on the Amundsen Sea continental shelf, Antarctica', *Geophysical research letters* [Preprint]. Available at: https://doi.org/10.1029/2008GL034939.

Thomas, R.H. (1979) 'The Dynamics of Marine Ice Sheets', *Journal of Glaciology*, 24(90), pp. 167–177.

Thompson, L.M. *et al.* (2021) 'Responding to ecosystem transformation: Resist, accept, or direct?', *Fisheries*, 46(1), pp. 8–21.

Formatted: Font color: Black

Formatted: Font color: Black

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Tietsche, S. *et al.* (2011) 'Recovery mechanisms of Arctic summer sea ice', *Geophysical research letters*, 38(2). Available at: https://doi.org/10.1029/2010gl045698.

Tilmes, S. *et al.* (2013) 'The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP)', *Journal of geophysical research*, 118(19), pp. 11,036–11,058.

Tilmes, S. *et al.* (2018) 'CESM1(WACCM) Stratospheric Aerosol Geoengineering Large Ensemble Project', *Bulletin of the American Meteorological Society*, 99(11), pp. 2361–2371.

Tilmes, S. *et al.* (2020) 'Reaching 1.5 and 2.0 °C global surface temperature targets using stratospheric aerosol geoengineering', *Earth system dynamics*, 11(3), pp. 579–601.

Tollefson, J. (2021) 'Can artificially altered clouds save the Great Barrier Reef?', *Nature*, pp. 476–478.

Touma, D. *et al.* (2023) 'The impact of stratospheric aerosol injection on extreme fire weather risk', *Earth's future*, 11(6). Available at: https://doi.org/10.1029/2023ef003626.

Trisos, C.H. *et al.* (2018) 'Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination', *Nature ecology & evolution*, 2(3), pp. 475–482.

Trusel, L.D. *et al.* (2015) 'Divergent trajectories of Antarctic surface melt under two twenty-first-century climate scenarios', *Nature geoscience*, 8(12), pp. 927–932.

Turetsky, M.R. *et al.* (2020) 'Carbon release through abrupt permafrost thaw', *Nature geoscience*, 13(2), pp. 138–143.

Turton, J.D. and Nicholls, S. (1987) 'A study of the diurnal variation of stratocumulus using A multiple mixed layer model', *Quarterly Journal of the Royal Meteorological Society*, 113(477), pp. 969–1009.

United Nations Environment Programme (2023) *One Atmosphere: An Independent Expert Review on Solar Radiation Modification Research and Deployment*.

Ushio, M. *et al.* (2020) 'Dynamic and synergistic influences of air temperature and rainfall on general flowering in a Bornean lowland tropical forest', *Ecological research*, 35(1), pp. 17–29.

Van Nes, E.H. *et al.* (2016) 'What do you mean,"tipping point"?', *Trends in ecology & evolution*, 31(12), pp. 902–904.

Visioni, D. *et al.* (2020) 'What goes up must come down: impacts of deposition in a sulfate geoengineering scenario', *Environmental research letters: ERL [Web site]*, 15(9), p. 094063.

Visioni, D. *et al.* (2021) 'Identifying the sources of uncertainty in climate model simulations of solar radiation modification with the G6sulfur and G6solar Geoengineering Model Intercomparison Project (GeoMIP) simulations', *Atmospheric Chemistry and Physics*, 21(13), pp. 10039–10063.

Wang, Q., Moore, J.C. and Ji, D. (2018) 'A statistical examination of the effects of stratospheric sulfate geoengineering on tropical storm genesis', *Atmospheric Chemistry and Physics*, 18(13), pp. 9173–9188.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Wang, S. *et al.* (2023) 'Mechanisms and impacts of earth system tipping elements', *Reviews of geophysics* , 61(1). Available at: https://doi.org/10.1029/2021rg000757.

Weertman, J. (1974) 'Stability of the Junction of an Ice Sheet and an Ice Shelf', *Journal of Glaciology*, 13(67), pp. 3–11.

Weijer, W. *et al.* (2020) 'CMIP6 models predict significant 21st century decline of the Atlantic meridional overturning circulation', *Geophysical research letters*, 47(12). Available at: https://doi.org/10.1029/2019gl086075.

Wise, M.G. *et al.* (2017) 'Evidence of marine ice-cliff instability in Pine Island Bay from iceberg-keel plough marks', *Nature*, 550(7677), pp. 506–510.

Wu, M. *et al.* (2021) 'Vegetation-climate feedbacks enhance spatial heterogeneity of pan-amazonian ecosystem states under climate change', *Geophysical research letters*, 48(8). Available at: https://doi.org/10.1029/2020gl092001.

Wunderling, N. *et al.* (2022) 'Recurrent droughts increase risk of cascading tipping events by outpacing adaptive capacities in the Amazon rainforest', *Proceedings of the National Academy of Sciences of the United States of America*, 119(32), p. e2120777119.

Xia, L. *et al.* (2016) 'Stratospheric sulfate geoengineering could enhance the terrestrial photosynthesis rate', *Atmospheric Chemistry and Physics*, 16(3), pp. 1479–1489.

Xie, M. *et al.* (2022) 'Impacts of three types of solar geoengineering on the Atlantic Meridional Overturning Circulation', *Atmospheric Chemistry and Physics*, 22(7), pp. 4581–4597.

Yang, B. *et al.* (2022) 'An elevation change dataset in Greenland ice sheet from 2003 to 2020 using satellite altimetry data', *Big Earth Data*, pp. 1–18.

Zanchettin, D. *et al.* (2014) 'Inter-hemispheric asymmetry in the sea-ice response to volcanic forcing simulated by MPI-ESM (COSMOS-Mill)', *Earth system dynamics*, 5(1), pp. 223–242.

Zarnetske, P.L. *et al.* (2021) 'Potential ecological impacts of climate intervention by reflecting sunlight to cool Earth', *Proceedings of the National Academy of Sciences of the United States of America*, 118(15). Available at: https://doi.org/10.1073/pnas.1921854118.

Zekollari, H., Huss, M. and Farinotti, D. (2019) 'Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble', *The cryosphere*, 13(4), pp. 1125–1146.

Zemp, D.C. *et al.* (2017) 'Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks', *Nature communications*, 8, p. 14681.

Zemp, M. *et al.* (2019) 'Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016', *Nature*, 568(7752), pp. 382–386.

Zhang, T., Osterkamp, T.E. and Stamnes, K. (1997) 'Effects of climate on the active layer and permafrost on the north slope of Alaska, U.s.a', *Permafrost and Periglacial Processes*, 8(1), pp. 45–67.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Zhang, Z., Jones, A. and James C., C.M. (2017) 'Impacts of stratospheric aerosol geoengineering strategy on Caribbean coral reefs', *International Journal of Climate Change Strategies and Management*, 10(4), pp. 523–532.

Zhao, L. *et al.* (2017) 'Glacier evolution in high-mountain Asia under stratospheric sulfate aerosol injection geoengineering', *Atmospheric Chemistry and Physics*, 17(11), pp. 6547–6564.

Zhou, S. *et al.* (2023) 'Slowdown of Antarctic Bottom Water export driven by climatic wind and sea-ice changes', *Nature climate change*, 13(7), pp. 701–709.

Zimov, S.A. (2005) 'Essays on science and society. Pleistocene Park: return of the mammoth's ecosystem', *Science*, 308(5723), pp. 796–798.

.

Stroeve, J. and Notz, D. (2015) 'Insights on past and future sea-ice evolution from combining observations and models', *Global and planetary change*, 135, pp. 119–132.

Surprise, K. (2020) 'Geopolitical ecology of solar geoengineering: from a "logic of multilateralism" to logics of militarization', *Journal of Political Ecology*, 27(1), pp. 213–235.

Sutter, J. *et al.* (2023) 'Climate intervention on a high-emissions pathway could delay but not prevent West Antarctic Ice Sheet demise', *Nature climate change*, 13(9), pp. 951–960.

Swapna, P. *et al.* (2017) 'Multidecadal weakening of Indian summer monsoon circulation induces an increasing northern Indian ocean sea level', *Geophysical research letters*, 44(20), pp. 10,560–10,572.

Swingedouw, D. *et al.* (2021) 'On the risk of abrupt changes in the North Atlantic subpolar gyre in CMIP6 models', *Annals of the New York Academy of Sciences*, 1504(1), pp. 187–201.

Táíwò, O.O. and Talati, S. (2022) 'Who are the engineers? Solar geoengineering research and justice', *Global environmental politics*, 22(1), pp. 12–18.

Tedesco, M. *et al.* (2016) 'The darkening of the Greenland ice sheet: trends, drivers, and projections (1981–2100)', *The cryosphere*, 10(2), pp. 477–496.

Telwala, Y. *et al.* (2013) 'Climate-induced elevational range shifts and increase in plant species richness in a Himalayan biodiversity epicentre', *PloS one*, 8(2), p. e57103.

Tietsche, S. *et al.* (2011) 'Recovery mechanisms of Arctic summer sea ice', *Geophysical research letters*, 38(2). Available at: https://doi.org/10.1029/2010gl045698.

Tilmes, S. *et al.* (2013) 'The hydrological impact of geoengineering in the Geoengineering Model Intercomparison Project (GeoMIP)', *Journal of geophysical research*, 118(19), pp. 11,036–11,058.

Tilmes, S. *et al.* (2018) 'CESM1(WACCM) Stratospheric Aerosol Geoengineering Large Ensemble

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Project', *Bulletin of the American Meteorological Society*, 99(11), pp. 2361–2371.

Tilmes, S. *et al.* (2020) 'Reaching 1.5 and 2.0 °C global surface temperature targets using stratospheric aerosol geoengineering', *Earth system dynamics*, 11(3), pp. 579–601.

Tollefson, J. (2021) 'Can artificially altered clouds save the Great Barrier Reef?', *Nature*, pp. 476–478.

Touma, D. *et al.* (2023) 'The impact of stratospheric aerosol injection on extreme fire weather risk', *Earth's future*, 11(6). Available at: https://doi.org/10.1029/2023ef003626.

Trisos, C.H. *et al.* (2018) 'Potentially dangerous consequences for biodiversity of solar geoengineering implementation and termination', *Nature ecology & evolution*, 2(3), pp. 475–482.

Trusel, L.D. *et al.* (2015) 'Divergent trajectories of Antarctic surface melt under two twenty-first-century climate scenarios', *Nature geoscience*, 8(12), pp. 927–932.

Turetsky, M.R. *et al.* (2020) 'Carbon release through abrupt permafrost thaw', *Nature geoscience*, 13(2), pp. 138–143.

Turton, J.D. and Nicholls, S. (1987) 'A study of the diurnal variation of stratocumulus using A multiple mixed layer model', *Quarterly Journal of the Royal Meteorological Society*, 113(477), pp. 969–1009.

United Nations Environment Programme (2023) *One Atmosphere: An Independent Expert Review on Solar Radiation Modification Research and Deployment*.

Van Nes, E.H. *et al.* (2016) 'What do you mean,"tipping point"?', *Trends in ecology & evolution*, 31(12), pp. 902–904.

Varikoden, H. *et al.* (2019) 'Contrasting trends in southwest monsoon rainfall over the Western Ghats region of India', *Climate Dynamics*, 52(7), pp. 4557–4566.

Visioni, D. *et al.* (2020) 'What goes up must come down: impacts of deposition in a sulfate geoengineering scenario', *Environmental research letters: ERL [Web site]*, 15(9), p. 094063.

Visioni, D. *et al.* (2021) 'Identifying the sources of uncertainty in climate model simulations of solar radiation modification with the G6sulfur and G6solar Geoengineering Model Intercomparison Project (GeoMIP) simulations', *Atmospheric Chemistry and Physics*, 21(13), pp. 10039–10063.

Wang, Q., Moore, J.C. and Ji, D. (2018) 'A statistical examination of the effects of stratospheric sulfate geoengineering on tropical storm genesis', *Atmospheric Chemistry and Physics*, 18(13), pp. 9173–9188.

Wang, S. *et al.* (2023) 'Mechanisms and impacts of earth system tipping elements', *Reviews of geophysics* , 61(1). Available at: https://doi.org/10.1029/2021rg000757.

Weertman, J. (1974) 'Stability of the Junction of an Ice Sheet and an Ice Shelf', *Journal of Glaciology*, 13(67), pp. 3–11.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Weijer, W. *et al.* (2020) ‘CMIP6 models predict significant 21st century decline of the Atlantic meridional overturning circulation’, *Geophysical research letters*, 47(12). Available at: https://doi.org/10.1029/2019gl086075.

van Wessem, J.M. *et al.* (2023) ‘Variable temperature thresholds of melt pond formation on Antarctic ice shelves’, *Nature climate change*, 13(2), pp. 161–166.

van Westen, R.M. and Dijkstra, H.A. (2023) ‘Asymmetry of AMOC hysteresis in a state-of-the-art global climate model’, *Geophysical research letters*, 50(22). Available at: https://doi.org/10.1029/2023gl106088.

Wise, M.G. *et al.* (2017) ‘Evidence of marine ice-cliff instability in Pine Island Bay from iceberg-keel plough marks’, *Nature*, 550(7677), pp. 506–510.

Wunderling, N., Winkelmann, R., *et al.* (2022) ‘Global warming overshoots increase risks of climate tipping cascades in a network model’, *Nature climate change*, 13(1), pp. 75–82.

Wunderling, N., Staal, A., *et al.* (2022) ‘Recurrent droughts increase risk of cascading tipping events by outpacing adaptive capacities in the Amazon rainforest’, *Proceedings of the National Academy of Sciences of the United States of America*, 119(32), p. e2120777119.

Wunderling, N. *et al.* (2024) ‘Climate tipping point interactions and cascades: a review’, *Earth system dynamics* [Preprint]. Available at: https://doi.org/10.5194/esd-15-41-2024.

Xia, L. *et al.* (2016) ‘Stratospheric sulfate geoengineering could enhance the terrestrial photosynthesis rate’, *Atmospheric Chemistry and Physics*, 16(3), pp. 1479–1489.

Xie, M. *et al.* (2022) ‘Impacts of three types of solar geoengineering on the Atlantic Meridional Overturning Circulation’, *Atmospheric Chemistry and Physics*, 22(7), pp. 4581–4597.

Yang, B. *et al.* (2022) ‘An elevation change dataset in Greenland ice sheet from 2003 to 2020 using satellite altimetry data’, *Big Earth Data*, pp. 1–18.

Zanchettin, D. *et al.* (2014) ‘Inter-hemispheric asymmetry in the sea-ice response to volcanic forcing simulated by MPI-ESM (COSMOS-Mill)’, *Earth system dynamics*, 5(1), pp. 223–242.

Zarnetske, P.L. *et al.* (2021) ‘Potential ecological impacts of climate intervention by reflecting sunlight to cool Earth’, *Proceedings of the National Academy of Sciences of the United States of America*, 118(15). Available at: https://doi.org/10.1073/pnas.1921854118.

Zekollari, H., Huss, M. and Farinotti, D. (2019) ‘Modelling the future evolution of glaciers in the European Alps under the EURO-CORDEX RCM ensemble’, *The cryosphere*, 13(4), pp. 1125–1146.

Zemp, D.C. *et al.* (2017) ‘Self-amplified Amazon forest loss due to vegetation-atmosphere feedbacks’, *Nature communications*, 8, p. 14681.

Zemp, M. *et al.* (2019) ‘Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016’, *Nature*, 568(7752), pp. 382–386.

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)

Zhang, T., Osterkamp, T.E. and Stamnes, K. (1997) 'Effects of climate on the active layer and permafrost on the north slope of Alaska, U.s.a', *Permafrost and Periglacial Processes*, 8(1), pp. 45–67.

Zhang, Z., Jones, A. and James C., C.M. (2017) 'Impacts of stratospheric aerosol geoengineering strategy on Caribbean coral reefs', *International Journal of Climate Change Strategies and Management*, 10(4), pp. 523–532.

Zhao, L. *et al.* (2017) 'Glacier evolution in high-mountain Asia under stratospheric sulfate aerosol injection geoengineering', *Atmospheric Chemistry and Physics*, 17(11), pp. 6547–6564.

Zhou, S. *et al.* (2023) 'Slowdown of Antarctic Bottom Water export driven by climatic wind and sea-ice changes', *Nature climate change*, 13(7), pp. 701–709.

Formatted: Justified

Formatted: Font: 10 pt

Formatted: Font: 10 pt

Formatted: Justified, Line spacing: Multiple 1.2 li, Border: Top: (No border), Bottom: (No border), Left: (No border), Right: (No border), Between : (No border)