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The interaction of solar radiation modification with Earth system tipping elements

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SUPPLEMENTARY INFORMATION OCEAN

Ocean circulation changes - tipping or weakening?

As briefly mentioned in the main text, for the discussed changes in ocean circulation, it is not certain whether they are indeed tipping points with the possibility of a collapse that might be irreversible or show hysteresis (fig. 1a-d), or whether the corresponding systems merely weaken without collapse (fig. 1e). In this SI, we briefly summarise the ongoing discussion on this matter. It should be noted, though, that

1) A strong weakening weakening of for example AMOC would have severe consequences, even if the weakening is not a full collapse
2) Such a weakening would not be instantly reversible, i.e. it may well be in place for decades or longer, given the long timescales of ocean processes, even if it would not be permanent as actual tipping might be
3) AMOC and SPG (and plausibly AABW) weakening have largely similar drivers to actual tipping. Hence an SAI measure that reduces AMOC weakening will likely reduce tipping risk.

Atlantic Meridional Overturning Circulation

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

Tipping – as opposed to merely weakening – requires that AMOC has a stable “off-state”, in which strong buoyancy forcing in the North Atlantic reduces surface density and prevents sinking. Starting with (Stommel, 1961), the possible presence of an off-state has been debated. However, it is uncertain whether AMOC can actually tip. Paleo evidence suggests AMOC has undergone rapid transitions (Lynch-Stieglitz, 2017), hinting at bi-stability. While conceptual or reduced-complexity ocean models show hysteresis under North Atlantic freshwater forcing (purple and green paths in fig. 3a), such experiments have long been prohibitively computationally expensive in state-of-the-art coupled models. Instead, modellers use hosing experiments, where large amounts of freshwater are dumped in the North Atlantic, to determine whether AMOC shuts down. Such experiments cannot distinguish a stable off-state from a prolonged, yet temporary shut-down (Gent, 2018; Rind *et al.*, 2018). (Jackson *et al.*, 2022) present multi-model experiments with unrealistically strong hosing. After hosing stops, AMOC does not recover in about half of these models, namely those in which AMOC had weakened below 5Sv. Recently, (van Westen, Kliphuis and Dijkstra, 2024) demonstrated that AMOC shows hysteresis in a full-fledged Earth System Model.

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 34ºS (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). (Liu *et al.*, 2017) find that AMOC becomes less stable in the CCSM3 model if biases are corrected. However, the ability of M_{ov} to diagnose AMOC stability is still under debate (Gent, 2018; Jackson *et al.*, 2022).

It is still unclear to what extent observational data can be used to detect AMOC weakening or tipping. Direct observations of AMOC strength (RAPID and OSNAP arrays) are too short and noisy to directly assess AMOC weakening (Lobelle *et al.*, 2020), let alone tipping. Several attempts have been made to reconstruct AMOC indices using variables with longer observational records. For example, (Caesar *et al.*, 2018) attempted to reconstruct AMOC from (surface-based) “fingerprints” and found it weakening, but (Worthington *et al.*, 2021) argue that (scarce) subsurface data is needed for a reliable reconstruction, and find no weakening since 1981. (Caesar *et al.*, 2021), using a set of proxies thought to also capture subsurface processes, find that AMOC is at its weakest state since 1000 years. (Ditlevsen and Ditlevsen, 2023) used an SST-based index to detect Early Warning Signals (EWS) of tipping based on increased variance and autocorrelation (critical slowing-down), but a study based on improved AMOC reconstructions (Michel, no date) find that the proposed EWS signals show a high amount of false positives. They do, however, find signs of AMOC weakening over the last century.

To summarise, it is uncertain whether AMOC has an off-state under current conditions.
AMOC does not need to actually tip in order to generate climate impacts. A prolonged quasi-stable shutdown or strong reduction in AMOC strength without complete shutdown could have severe climate impacts even without actual tipping , which could last for decades (fig. 4 of (Loriani *et al.*, 2023))

North Atlantic Subpolar Gyre

As mentioned in the main text, main drivers are therefore surface warming and processes leading to surface freshening. As for AMOC, it is uncertain whether the SPG can actually tip.

(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. Compared to AMOC, there are few dedicated studies on SPG tipping and less discussion about whether the SPG could weaken strongly without tipping.

Although SPG collapse can occur without AMOC collapse, the two systems 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.

Antarctic Bottom Water formation

(Armstrong McKay *et al.*, 2022) list a cessation or strong reduction of AABW formation as a potential Global tipping element ("global" because it could affect the global ocean circulation); Loriani et al. (2023) classify Southern Ocean Circulation as tipping point with medium confidence. (Lago and England, 2019) adapted an ocean model to represent freshwater inflow from Antarctic ice melt following the assumptions of (DeConto and Pollard, 2016) as an extreme case. They found that under meltwater inflow representing RCP4.5 and RCP8.5 scenarios, AABW shuts down within 50 years, while it is significantly reduced under RCP2.6. As most models do not represent ice melt, (Armstrong McKay *et al.*, 2022) categorise the effect only as "potential" tipping element. Fox-Kemper *et al.* (2021) assigns medium confidence to the prediction that the lower circulation cell in the Atlantic will decrease through the 21st century as a result of Antarctic ice sheet melt, but does not predict a tipping point or complete shut-down. (Li *et al.*, 2023) predict a strong weakening by 2050 under RCP8.5.

Generally, process understanding is poor, not least because relevant small-scale processes, especially ice shelf basal melt, are not appropriately modelled in ESMs.

Other Tropical Forests: The Dipterocarp forests of Southeast Asia as an example

The tropical forests of the Amazon are not the only reservoirs of biodiversity, of course, and are not the only tropical forests that might experience tipping points or their prevention as a result of SRM. 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 may be considered to precipitate tipping points, although this hypothesis is very tentative and needs much more evidence. 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.

S.X.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 another state, such as grassland or savannah, and likely one much lower in biotic diversity. These forests are also threatened by clearcutting, particularly to establish oil palm plantations, and resilience may be compromised by fragmentation and size reduction preventing effective tree reproduction, although it is not clear whether regime shifts per se actually occur (Nikonovas *et al.*, 2020)(Numata *et al.*, 2022).

S.X.2: The impacts of SRM

SRM is predicted to reduce average global mean temperatures and create drier conditions globally (MacMartin *et al.*, 2016) including in southeast Asia ((Tan *et al.*, 2023) that might counteract much of the impacts of climate change on these forests. (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 (possible) climate-induced tipping points that prevent tree regeneration and lead to an alternative, tree-less state as grassland or savannah. 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). The unique dependence of tree regeneration to very specific temperature cues makes them uniquely senesitive to potential climate-induced tipping, and other forcing leading to fire and fragmentation exacerbate this vulnerability. SRM could conceivably pull this system back from at least the forcing due to warm nights, but this is by no means certain and with the limited data available, remains conjecture.

S.X.3. Further Research

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

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