Effect of Regional Marine Cloud Brightening Interventions on Climate Tipping Elements

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Key Points:

- The magnitude and pattern of marine cloud brightening (MCB) climate impacts depend strongly on the location of the intervention
- We find MCB impacts that have qualitative similarities to prior work, but there are discrepancies that suggest key inter-model uncertainties
- The MCB impact generally indicates reduced tipping element risk overall, but certain intervention patterns may exacerbate some tipping element changes

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Abstract

It has been proposed that increasing greenhouse gas (GHG) driven climate tipping point risks may prompt consideration of solar radiation modification (SRM) climate intervention to reduce those risks. Here, we study marine cloud brightening (MCB) SRM interventions in three subtropical oceanic regions using Community Earth System Model 2 (CESM2) experiments. We assess the MCB impact on tipping element-related metrics to estimate the extent to which such interventions might reduce tipping point risk. Both the pattern and magnitude of the MCB cooling depend strongly on location of the MCB intervention. We find the MCB cooling effect reduces most tipping element impacts; though differences in MCB versus GHG climate response patterns mean MCB is an imperfect remedy. However, MCB applied in certain regions may exacerbate certain GHG tipping element impacts. Thus, it is crucial to carefully consider the pattern of MCB interventions and their teleconnected responses to avoid unintended climate effects.

Plain Language Summary

Marine cloud brightening (MCB) is a proposal to spray sea salt particles into clouds over oceans to increase the reflection of sunlight by the clouds, thus cooling the surface. If greenhouse gas warming continues, technologies like MCB might be considered to avoid climate change impacts such as climate system tipping points. Here, we use state-of-the-art climate model experiments to analyse the MCB impact on elements of the climate system that may have tipping points. In this model, MCB reduces risks for most tipping elements considered here, such as reducing coral reef heat stress and increasing Atlantic overturning circulation. However, the impact of MCB depends where it is applied, meaning the location of MCB deployments must be carefully considered to avoid unintended regional climate effects.

1 Introduction

Current net-zero pledges are projected to cause approximately 2°C of warming above pre-industrial (Meinshausen et al., 2022), a level of warming at which there is a substantial risk of crossing thresholds that could trigger tipping points: qualitative changes in the development of some elements of the climate system that result in rapid or even irreversible changes to regional and global climate (Armstrong McKay et al., 2022). Given that mitigation may proceed slower than planned, that climate sensitivity may be higher than expected, and/or that some tipping points may be more sensitive than anticipated, climate interventions may be considered to avert catastrophic impacts. One class of climate intervention methods known as solar radiation modification (SRM) has been proposed as a means to reduce warming impacts on elements of the climate system with tipping points (termed tipping elements), as SRM could rapidly reduce surface temperatures (Society, 2009; National Academies of Sciences, Engineering, and Medicine, 2021; United Nations Environment Programme, 2023). Past studies have examined SRM impacts on specific tipping elements, such as West Antarctic ice sheets (McCusker et al., 2015), Greenland ice Sheets (Applegate & Keller, 2015), and coral reefs (Latham et al., 2013). However, Earth System Model (ESM) studies suggest SRM interventions are imperfect methods for counteracting GHG-induced climate change impacts, in part due to distinct spatial distributions of the climate responses. Thus, in this study we seek to more holistically assess if SRM might indeed reduce tipping point risks by evaluating impacts across a range of tipping elements.

We use state-of-the-art ESM experiments to assess one such proposed SRM technique, marine cloud brightening (MCB). MCB aims to increase marine boundary layer cloud albedo by emitting sea salt aerosol in certain oceanic regions. Assuming fixed liquid water amount, these aerosols would act as cloud condensation nuclei (CCN), increasing cloud droplet number concentrations (CDNC), decreasing cloud droplet radii, and increasing cloud albedo (Twomey, 1977). This ultimately cools surface temperatures, leading to this mechanism being proposed as a means to reduce GHG warming impacts (Latham, 1990; Latham et al., 2012). These changes in CDNC can also induce changes in cloud water content and cloud lifetime that can enhance or diminish the CDNC brightening effect (Albrecht, 1989; Alterskjaer & Kristjánsson, 2013), though it may be possible to design MCB strategies to avoid aerosol injections that would cause cloud darkening (Hoffmann & Feingold, 2021; Wood, 2021).

Compared to stratospheric aerosol injections (SAI) which cause forcing over broad zonal bands (Tilmes et al., 2017), MCB cloud responses are highly localized due to the short atmospheric lifetime of tropospheric aerosols and aerosol impacts on cloud properties. The associated radiative response to MCB-induced aerosol and cloud changes (MCB forcing) will also be localized (Latham et al., 2012). Thus, there is a range of possible MCB forcing patterns which would have differing regional climate impacts. However, because much of the large scale climate response to MCB will be remote responses to localized forcings, the large scale climate response will be the result of teleconnections which have uncertainties across ESMs that may induce unintended climate impacts (Diamond et al., 2022).

Past studies of MCB climate impacts have taken two main approaches. The first applies uniform MCB perturbations over all oceans (Latham et al., 2008; Bala et al., 2011; Kravitz et al., 2013; Stjern et al., 2018; Duan et al., 2018) or over low-latitude oceans (Alterskjær et al., 2013; Muri et al., 2018). The second focuses MCB perturbations in regions with high concentrations of marine low clouds, typically in subtropical regions at the eastern boundaries of oceanic basins (Rasch et al., 2009; Jones et al., 2009; Korhonen et al., 2010; Partanen et al., 2012; Hill & Ming, 2012; Stuart et al., 2013; Baughman et al., 2012), as MCB is typically expected to be most effective in shallow marine stratocumulus cloud deck regions (Rasch et al., 2009; Latham et al., 2012). Here we consider a protocol of the latter type, since MCB interventions will likely focus on regions where sea salt emissions most efficiently achieve cooling. Though observational evidence suggests that clouds in other regions such as the midlatitude North Pacific are also susceptible to brightening (Watson-Parris et al., 2022; Zhang & Feingold, 2023).

We use a protocol similar to those used by Jones et al. (2009) and Hill and Ming (2012). In these studies, MCB perturbations are applied to the three regions with the most extensive marine stratocumulus cloud decks (the subtropical Northeast Pacific - NEP, Southeast Pacific - SEP, and Southeast Atlantic - SEA). Both studies showed substantial differences in the global mean and pattern of climate response to MCB, depending on which region is perturbed. These studies used Coupled Model Intercomparison Project 3 (CMIP3) generation models and consequently lack improvements made in ESMs since. For example in the ESM used here, changes to parameterizations (i.e., for clouds and convection) have improved representation of precipitation and temperature climatologies, among other improvements (Danabasoglu et al., 2020). Thus, our ESM experiments provide an updated analysis of the MCB climate responses in the three regions using a state-of-the-art CMIP6-generation ESM and provide a novel investigation of MCB effect on key climate tipping element metrics (TEMs).

2 Methods

2.1 Earth System Model Experiments

Our experiments are conducted using the Community Earth System Model 2 (CESM2; Danabasoglu et al., 2020). MCB forcing is approximated by prescribing the in-cloud stratiform liquid CDNC as a constant value at all vertical levels over ocean grid points in the Southeast Pacific (SEP - 30S to 0, 110W to 70W), Northeast Pacific (NEP - 0 to 30N, 150W to 110W), and Southeast Atlantic (SEA - 30S to 0, 25W to 15E) (Red boxes in Fig. 1a). That is, we assume sea salt injections will increase CDNC as hypothesized and study the climate responses of such cloud perturbations, similar to past studies (Rasch et al., 2009; Jones et al., 2009; Kravitz et al., 2013; Stjern et al., 2018). We select these regions as past work has found they have high marine stratocumulus cloud fractions, though observational evidence shows parts of the SEP and SEA regions may feature some clouds that darken in response to CDNC increases in part of the year (Zhang & Feingold, 2023). Perturbing CDNC throughout the column is idealized. However, as CDNC is only perturbed in existing stratiform liquid clouds, we are principally perturbing warm marine boundary layer cloud regimes. Though the method also has small effects on higher-altitude mixed phase and convective clouds.

We specify the strength of the CDNC increase in the three regions (SEP, NEP, and SEA) such that the MCB effective radiative forcing (ERF) is -1.8Wm^{-2}, approximately half the forcing due to a doubling of CO_2 (Smith et al., 2018). Using fixed SST simulations, we find we achieve this when prescribing CDNC to 600cm^{-3} in the three regions (ERF $= -1.8 \pm 0.1$Wm^{-2}) (2-standard error uncertainty). If we set CDNC to 600cm^{-3} in each of the regions individually, we find ERFs of -0.7 ± 0.1Wm^{-2} for the SEP, -0.6 ± 0.1Wm^{-2} for the NEP, and -0.5 ± 0.1Wm^{-2} for the SEA (Fig. 1a). The sum of the NEP, SEP, and SEA ERFs approximately equals the ALL MCB ERF, thus we do not find evidence of forcing non-linearity (in contrast to Jones et al. (2009), but in similar to Boucher et al. (2017), who found MCB and SAI forcings were additive). We note that CDNC equal to 600cm^{-3} is likely not attainable in practice (Alterskjaer & Kristjánsson, 2013). Furthermore, MCB experiments using sea salt emission changes show that much of radiative forcing is due to direct aerosol scattering, rather than cloud brightening (Ahlm et al., 2017; Mahfouz et al., 2023). However, we argue that the precise implementation of the regional shortwave forcing has only modest effects on the large scale climate response, as we find few significant differences in the CESM2 coupled climate response to these CDNC perturbations versus sea salt emission increases with similar forcing location and magnitude (Fig. S1).

We assess the MCB climate response using idealized coupled CESM2 scenarios with a SSP2-4.5 baseline forcing and set CDNC to 600cm^{-3} in all three regions simultaneously (ALL MCB) and each region separately (SEP, NEP, SEA) from 2015 to 2064. SSP2-4.5 is chosen as the baseline emission scenario following GeoMIP (Kravitz et al., 2015) and ARISE-SAI (Richter et al., 2022). Three ensemble members are simulated in each MCB forcing case. To compare the MCB climate responses (SSP2-4.5 with MCB minus SSP2-4.5) to the SSP2-4.5 climate response, we compute anomalies for the decade during which the SSP2-4.5 global mean surface temperature (GMST) warming from the 1995-2014 historical baseline is equal and opposite to the ALL MCB cooling relative to SSP2-4.5 (2034-2044, see GMST anomalies in titles of Fig. 2a,b). Thus we approximate a case in which ALL MCB (NEP, SEP, and SEA) is deployed to stabilize GMST to early 21st century levels. For the historical baseline, we use the CESM2 Large Ensemble historical smoothed biomass burning experiments (see Rodgers et al., 2021). The coupled CESM2 experiments we use are summarized in Table 1. Statistical significance is tested using the Student's t-test with a p-value threshold as the lesser of $p < 0.05$ and the false discovery rate $p < p_{fdr}$ ($\alpha = 0.1$) for anomaly maps (Wilks, 2016).

2.2 Tipping elements

Climate tipping points occur when a part of the climate system is in a state where a small perturbation can cause substantial qualitative alterations to the state or development of that system (Lenton et al., 2008; Armstrong McKay et al., 2022). In section 4, we assess the MCB effect on regional climate metrics associated with 14 elements of the climate system (tipping elements) that were identified to have potential tipping points by Armstrong McKay et al. (2022) (TEMs). We do not assess tipping elements with lower-bound threshold elements over 4C and those that require offline modeling (see discussion in section S1). The definitions for these TEMs are discussed in sections S1-S10 and summarized in Table S1. Owing to difficulties in process representation, there is significant uncertainty in the representation of tipping elements within ESMs (Drijfhout et al., 2015; Wang et al., 2023). Like many ESMs, CESM2 does not represent processes that drive certain tipping points. For example, the configuration used here does not include

Table 1. Coupled CESM2 experiments used in this work

Experiment name	Configuration	Baseline Forcing	MCB forcing	Years	Members
Historical LE	Coupled CESM2	Historical with smoothed biomass burning	None	1850 - 2014	50
SSP2-4.5 LE	Coupled CESM2	SSP2-4.5	None	2015 - 2100	17
ALL MCB	Coupled CESM2	SSP2-4.5	600cm^{-3} in NEP, SEP, SEA	2015 - 2064	3
NEP	Coupled CESM2	SSP2-4.5	600cm^{-3} in NEP	2015 - 2064	3
SEP	Coupled CESM2	SSP2-4.5	600cm^{-3} in SEP	2015 - 2064	3
SEA	Coupled CESM2	SSP2-4.5	600cm^{-3} in SEA	2015 - 2064	3

dynamic ice sheets, nor does it include dynamic forest cover (a key factor in Amazon and Sahel feedbacks). Furthermore, although the tipping elements assessed here have minimum tipping point threshold estimates of 3C warming from preindustrial or lower (and thus may be crossed under SSP2-4.5 warming), the central threshold estimates are not reached under SSP2-4.5 warming in most cases (Armstrong McKay et al., 2022). Thus, the TEM changes herein can only be interpreted as the tendency of anthropogenic GHG emissions to instigate a tipping point and the effect of MCB interventions on that tendency, as direct assessments of tipping point risks are largely not possible. Nevertheless, assessing the relative effects of MCB interventions on these key regional tipping element related climate indicators provides insight into the benefits and risks associated with different MCB intervention strategies.

3 Results

The GMST and precipitation (GMPR) effects of 600cm^{-3} MCB interventions are shown in Fig. 1b, c. For the 2020 to 2060 average, we find that the ALL MCB forcing in CESM2 causes a -1.05 ± 0.02K (2-standard error uncertainty) GMST cooling relative to SSP2-4.5. Like Jones et al. (2009) and Hill and Ming (2012), we find that SEP forcing is the largest driver of cooling at -0.77 ± 0.02K in CESM2. However, we find relatively weaker NEP (-0.20 ± 0.02K) and SEA (-0.02 ± 0.02K) cooling, than previous studies. The sum of GMST effects from the three regions is -0.98 ± 0.04K. Thus, there is a modest, but statistically significant non-linearity in the global cooling effects. Because the areal extent and ERF of each region is similar, the divergent GMST cooling signals suggest large differences in temperature sensitivity to MCB forcing between the regions (NEP: 0.31 ± 0.05Km^2/W; SEP: 1.03 ± 0.07Km^2/W; SEA: 0.04 ± 0.08Km^2/W) and thus a key role of the pattern effect in radiative feedbacks (Stevens et al., 2016). For GMPR (Fig. 1c), there is a higher hydrological sensitivity for MCB compared to SSP2-4.5 warming (-0.087mm/day/K for ALL MCB vs. 0.061mm/day/K for SSP2-4.5), consistent with other shortwave forcings i.e., SAI (Bala et al., 2008; Tilmes et al., 2013; Duan et al., 2018) and historical tropospheric sulphate aerosol emissions (Andrews et al., 2010; Samset et al., 2016; Myhre et al., 2017).

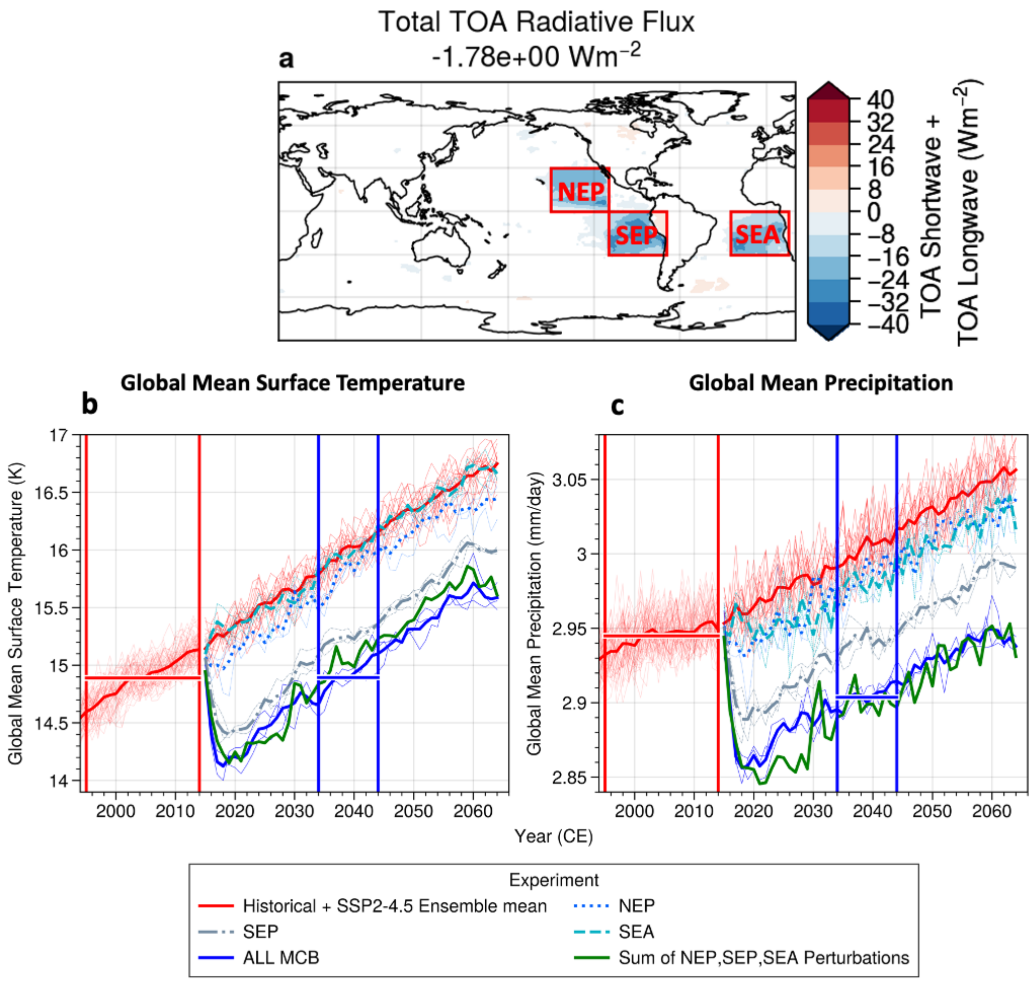

Figure 1. Annual mean top of atmosphere (TOA) net radiative flux anomalies (a) (non-significant grid points are masked in white and hatched, $p > p_{fdr} = 0.007$). NEP, SEP, and SEA regions shown in red boxes. Global annual mean surface temperature (b) and precipitation (c) in the CESM2 historical and SSP2-4.5 experiments (red) and SSP2-4.5 + MCB experiments (ALL MCB - dark blue; NEP - light blue; SEP - grey-blue; SEA - turquoise). Thick lines show ensemble means and thin lines show individual ensemble member. The solid green line shows the sum of ensemble mean anomalies for the individual NEP, SEP, and SEA experiments relative to SSP2-4.5 plus the SSP2-4.5 ensemble mean.

3.1 Regional Climate Response to MCB Intervention

Our experiments indicate that ALL MCB forcing would cause temperature anomalies that strongly resemble composite La Niña SST anomalies (e.g., Fig. 14 in Danabasoglu et al. (2020)) with tropical Pacific cooling and warming in regions such as the Kuroshio

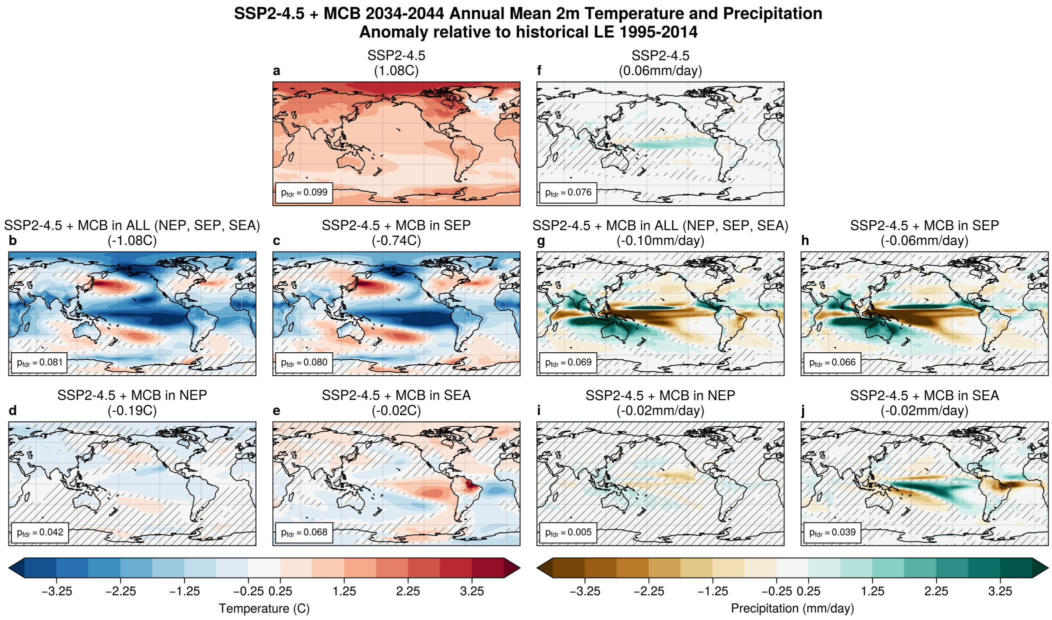

Figure 2. Annual mean 2m temperature (left side: a-e) and precipitation (right side: f-j) anomaly maps. Top two panels show the 2034-2044 SSP2-4.5 anomaly from the historical 1995-2014 baseline (a,f). The bottom eight panels show the 2034-2044 mean of the MCB simulations minus the 2034-2044 SSP2-4.5 mean for ALL MCB (b,g), SEP (c,h), NEP (d,i), and SEA (e,j). Red boxes indicate MCB forcing regions. Global mean anomalies are shown in parentheses above each panel. Non-significance is denoted by gray hatching. p_{fdr} shown in bottom left of each panel.

and Gulf stream extensions (Fig. 2b). The SEP experiment also shows a strong La Niña-like response pattern, indicating the ALL MCB effect is mainly due to SEP MCB (Fig. 2c). The NEP experiment shows cooling in the northern hemisphere (NH) generally, with warming in patches of the midlatitude North and South Pacific (Fig. 2d). The SEA experiment shows cooling in the tropical Atlantic and warming in the tropical east Pacific, northern South America, and the NH generally (Fig. 2e). Thus, for CESM2, the MCB forcings tested here amplify SSP2-4.5 warming in some regions. Conversely, there are many regions where MCB cooling is stronger than SSP2-4.5 warming even when the GMST responses are equal and opposite, resulting in colder conditions than the historical baseline.

The ALL MCB precipitation response also resembles La Niña composite (again primarily due to the SEP forcing; Fig. 2g,h), with strong tropical Pacific drying and wetting on the poleward flanks of the Pacific and Indian ocean inter-tropical convergence zones (ITCZ). Over land, the SEP experiment shows wetting in Australian, South and East Asian, and West African monsoon regions and drying in tropical central Africa and midlatitude regions such as North America, Europe, southern Africa, and southern South America. The NEP experiment shows drying locally in the NEP forcing region (Fig. 2i). The SEA experiment shows a northward shift of the Atlantic ITCZ, with drying in the south of the equator and in the Amazon and wetting north of the equator and in West Africa (Fig. 2j), plus tropical Pacific wetting and drying in poleward flanks of the Pacific ITCZ.

The CESM2 responses here bear broad qualitative similarities to previous HadGEM2 results (Jones et al., 2009), such as the SEP La Niña-like response and SEA Amazon drying. However, we also find key differences between the models. Midlatitude warming, central African drying, and land monsoon wetting signals in the CESM2 SEP response are absent or much weaker in HadGEM2 versus CESM2. While north and tropical Pacific cooling due to NEP is weaker in CESM2. These discrepancies are partially due to differences in forcing region definitions and forcing amount. However, the MCB ERF for each region in Jones et al., 2009 differs from the CESM2 simulations by at most $0.2\mathrm{Wm}^{-2}$, meaning teleconnection uncertainties likely play an important role.

3.2 Tipping Element Metric Response to MCB Intervention

Fig. 3 shows colour wheels displaying SSP2-4.5 and MCB forcing impacts on each selected climate TEMs. The SSP2-4.5 impact is computed as the 2034-2044 minus 1995-2014 anomaly. The MCB impacts are computed as the SSP2-4.5 + MCB minus SSP2-4.5 anomaly for 2034-2044. Thus, we compare ALL MCB to SSP2-4.5 at a period when their GMST impacts are approximately equal and opposite, meaning cases where the ALL MCB ring shows equally intense but opposite coloured anomalies to the SSP2-4.5 ring indicate MCB has neutralized the effect of SSP2-4.5. Pink colours indicate tipping element changes indicating increased risk and green colours indicate reduced risk. The pink colours across the outer rings indicate overall increases in tipping element risk under SSP2-4.5, except for Sahel precipitation (Fig. 3i). The weak Sahel precipitation effect is likely a model dependent signal, as there is model uncertainty regarding the sign of the GHG precipitation impact in the region (Gaetani et al., 2017; Monerie et al., 2020).

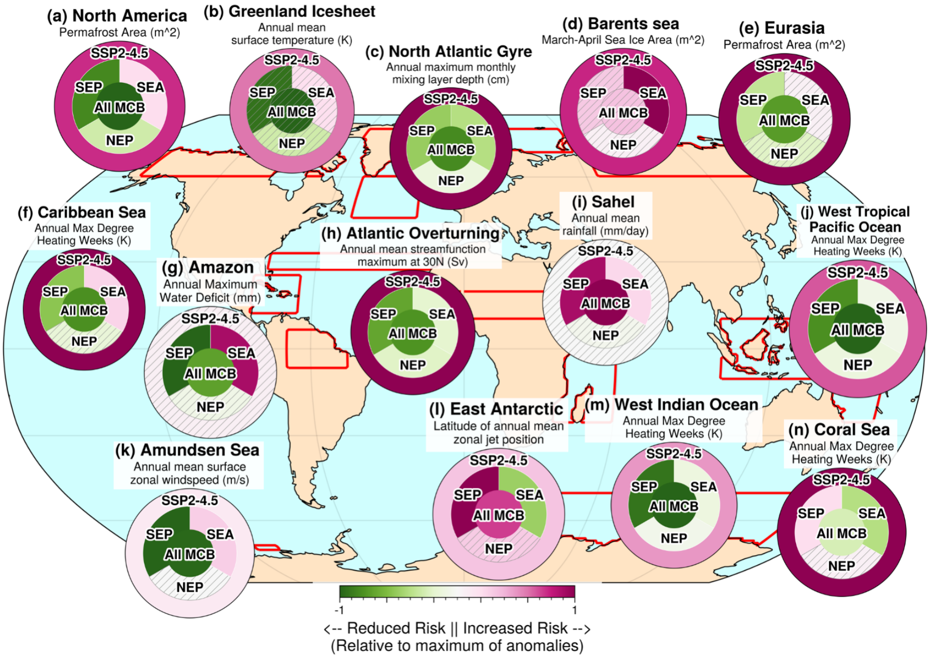

Figure 3. Effects of SSP2-4.5 and MCB forcing on the 14 selected tipping element metrics shown using a wheel for each metric (a-n) with each section representing a different experiment and colours indicating the relative anomalies for each TEM and experiment (See supplementary material for definitions, Fig. S2 for time series and Fig. S3 for absolute changes). Pink indicates increased tipping element risk and green indicates decrease tipping element risk. The 2034-2044 SSP2-4.5 anomaly relative to the historical 1995-2014 baseline is shown in the outer ring. The second, intermediate, ring shows the anomaly for the individual SEP, NEP, and SEA MCB simulations minus SSP2-4.5 for 2034-2044 (top left - SEP, bottom - NEP, top right - SEA). The inner circle shows the anomaly for ALL MCB minus SSP2-4.5 for 2034-2044. The colour scale of each wheel is scaled to the maximum of anomalies of SSP2-4.5 and the four MCB experiments. Hatching indicates where the anomalies are insignificant, $p > 0.05$, by a Student's t-test.

Impacts from MCB interventions are more heterogenous and complex. The ALL MCB cooling results in statistically significant TEM changes that indicate reduced risk for most temperature related tipping elements. Our experiments show reduced North American/Eurasian permafrost loss (Fig. 3a,e), Greenland warming (Fig. 3b), and coral heat stress in the Caribbean sea (Fig. 3f), West Tropical Pacific (Fig. 3j), West Indian ocean (Fig. 3m), and Coral sea (Fig. 3n). We also find significant circulation responses with reduced Amundsen sea zonal wind speed (Fig. 3k), indicating reduced West Antarctic ice sheet melt, and increased AMOC index and North Atlantic gyre mixing depth (Fig. 3c,h), indicating reduced AMOC collapse risk. Furthermore, we see reductions in annual maximum Amazon water deficit (Fig. 3g), indicating reduced Amazon rainforest drought risk. However, the ALL MCB experiment shows negligible effects on Barents Sea winter sea ice area (Fig. 3d), an increase in Sahel rainfall indicating increased Sahel greening risk (Fig. 3i), and a poleward shift of the extratropical jet off of the East Antarctic ice sheet (Fig. 3l), which is associated with increased warm water upwelling near East Antarctic ice shelves (Fogwill et al., 2014). Due to the differing climate response patterns for ALL MCB versus GHG despite the balance in GMST changes, MCB does not mask the entire SSP2-4.5 signal in many TEMs (Fig. 3c, e, f, h, n). For others, the MCB response exceeds the SSP2-4.5 response (Fig. 3a,b,g,i,j,k,m), sometimes quite substantially, such as for Amundsen sea zonal wind speed where ALL/SEP MCB shows a strong decrease.

We find the ALL MCB changes are largely related to SEP forcing for all TEMs except Coral sea heat stress (where we see local warming; Fig. 3n). NEP forcing causes NH cooling, thus NH TEMs generally shift to indicate reduced risk, and NEP has negligible effects on TEMs in all other cases. Conversely, the SEA forcing experiment shows NH warming thus indicating increased tipping element risk for Barents winter sea ice area (Fig. 3d), North American permafrost (Fig. 3a), and Caribbean sea coral heat stress (Fig. 3f). Furthermore, Amazon rainfall reductions in the SEA experiment substantially increase the Amazon moisture deficit, increasing forest dieback risk (Fig. 3g), which is offset by moisture deficit decreases in the SEP and NEP experiments. The SEA experiment also shows AMOC strengthening and reduced Coral sea heat stress, the latter of which counteracts the warming effect of SEP forcing.

4 Discussion

In this study, we have conducted CESM2 experiments to explore the climate responses to marine cloud brightening in three regions known for their extensive marine stratus and stratocumulus cloud decks. Our experiments provide a novel assessment of a key set of MCB intervention scenarios that have not been studied since CMIP3-generation models (Jones et al., 2009; Rasch et al., 2009; Hill & Ming, 2012). These scenarios are distinct from globally uniform interventions (Kravitz et al., 2013; Stjern et al., 2018), as they target regions with clouds that can be more efficiently brightened (Rasch et al., 2009; Latham et al., 2012). Our study reaffirms that MCB has the potential to reduce many of the climate effects of GHG warming. This includes a range of climate tipping element metrics which suggest a reduction in the risk of crossing most tipping point thresholds when MCB is applied in all three regions we considered here.

As noted in previous studies, both the pattern and magnitude of the climate response to MCB forcing strongly depends on the location of the forcing (Jones et al., 2009; Hill & Ming, 2012). We find many qualitative similarities compared to these prior studies, although CESM2 appears to have a lower GMST sensitivity to NEP and SEA forcing. The pattern of MCB climate response is distinct from the GHG impact, such that there are residual changes even when global temperature effects of SSP2-4.5 forcing and MCB are equal and opposite. Indeed, CESM2 suggests that MCB in some regions could induce warming (likely circulation-driven) in parts of the globe, though this effect is less pronounced in other models (Jones et al., 2009; Hill & Ming, 2012). Thus, model representations of the pattern effect in radiative feedbacks and circulation climatology/changes play key roles in determining the climate response to MCB.

Furthermore, our experiments suggest that MCB could reduce the risk of crossing many tipping point thresholds, as the ALL MCB experiment (forcing in all three regions considered here) shows reductions across most of the tipping element impacts we considered. Except in the cases of Sahel greening and East Antarctic zonal jet latitude, where ALL MCB intervention exacerbates the SSP2-4.5 impact. However, the intervention is imperfect, as the ALL MCB over-corrects some TEMs and under-corrects others relative to SSP2-4.5. Over-cooling may have negative consequences of its own, such as for coral mortality which can increase under cold conditions (Kemp et al., 2011).

The MCB effect on TEMs is sensitive to pattern of the forcing such that some cases may exacerbate the SSP2-4.5 effect. For example, our SEA experiment shows substantially reduced rainfall in eastern Brazil, increasing the risk of drought and rainforest dieback in the region (as also noted by Jones et al. (2009)). However, some of these regional effects are non-additive, such that MCB in SEA might be considered in combination with MCB in other regions. In addition, ESMs have substantial biases across many tipping elements and may represent key processes insufficiently or not at all, making tipping points an important uncertainty for both GHG and SRM climate impacts. Furthermore, the distinct pattern of MCB climate response necessitates holistic assessment across a range of tipping elements and scenarios to evaluate MCB as an intervention option. On the other hand, the large possibility space of MCB intervention patterns leaves open the potential to identify specific MCB intervention patterns that could reduce tipping element risks while minimizing unintended negative impacts.

Though we only assess one model here, the differences in the global mean and pattern of MCB climate responses between this and past studies suggest important intermodel uncertainties due to differences in climate feedbacks, atmosphere-ocean circulation, and MCB implementation. Because many of the desired responses to MCB would occur away from the forcing regions themselves, it is crucial that circulation uncertainties are understood and reduced in order to evaluate the feasibility of MCB interventions (Diamond et al., 2022). Furthermore, our experiments model MCB perturbations by directly changing in-cloud CDNC, which neglects sea salt direct aerosol forcing and the effect of aerosol transport on the forcing patterns (Partanen et al., 2012; Ahlm et al., 2017). While we expect that the remote response to MCB interventions will be mostly insensitive to the specifics the MCB shortwave forcing in a given region (as shown in Fig. S1), there may be important direct impacts of sea salt aerosol, such as effects on atmospheric chemistry (Horowitz et al., 2020). In addition, CESM2 has among the highest aerosol-cloud interaction effects in the CMIP6 ensemble (Smith et al., 2020), meaning the CDNC perturbations used herein may result in weaker forcing in other models. These issues highlight a need for systematic assessment of the forcing and climate response of MCB interventions in high susceptibility regions and the role of different sources of uncertainty across ESMs. Evaluating such uncertainties will be a key aim of a forthcoming multi-model intercomparison of regional MCB applications.

Open Research Section

CESM2 code modifications and model output and analysis scripts available on Zenodo at https://doi.org/10.5281/zenodo.8184798, CC BY-NC-SA 4.0. CESM2 LE historical and SSP2-4.5 data are provided by the National Center for Atmospheric Research https://www.cesm.ucar.edu/community-projects/lens2/data-sets.

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