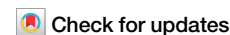




Marine cloud brightening mitigates the warming induced by the aerosol reductions toward carbon neutrality



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Marine cloud brightening (MCB), a geoengineering strategy that increases the cloud albedo, is potentially able to reduce the impacts of global warming. We simulate an MCB strategy to offset the warming induced by anthropogenic aerosol reduction following the Shared Socioeconomic Pathway 1-1.9 carbon-neutral scenario. Injecting sea salt aerosol into four cloudy regions in the eastern Pacific Ocean every year from 2020 to 2100 effectively restrains the future global-mean surface air temperature and precipitation change to the 2020 level. Aerosol-cloud interaction dominates the cooling in this MCB strategy. However, this strategy does not fully offset the warming in Europe, the United States, northeastern China and downwind offshore oceans, partly related to the acceleration of the Atlantic Meridional Overturning Circulation driven by the MCB-induced hemispherical asymmetric radiation gradients. Considering both the anthropogenic aerosol reductions and the MCB sea salt injection, some regions would face unintended climate change. Our study highlights the need for a more careful implementation strategy to produce both widespread cooling and fewer regional climate risks considering the effects are highly dependent on the strategy and seeding location.

Global warming is expected to have negative impacts on the climate system including Greenland and west Antarctic ice sheet collapse, ocean acidification, sea level rise, and increased extreme weather, which are detrimental to sustainable social and economic development^{1,2}. Despite conventional mitigation measures, such as reducing greenhouse gas emissions, being implemented, those measures are still insufficient to mitigate the devastating effects of climate change^{3,4}. Solar Radiation Management has been proposed as a potential temporary solution to counteracting global warming by reducing the amount of solar radiation reaching the Earth's surface⁵. In addition to stratospheric aerosol injection, the strategy of Solar Radiation Management through perturbing low-level oceanic clouds, which is called marine cloud brightening (MCB), has received widespread attention.

MCB refers to brightening marine stratocumulus clouds by seeding the lower atmosphere with sea salt aerosols (SSA)⁶. Theoretically, the injected aerosols increase CDNC, forming smaller droplets that enhance cloud

albedo. Observation of ship tracks⁷⁻¹⁰, increased low clouds by Kilauea volcanic aerosol plume¹¹ and increased CDNCs due to Holuhraun volcanic aerosols¹² have confirmed that clouds become more reflective with increasing aerosols. The abruptly reduced sulfur dioxide emissions from international shipping due to International Maritime Organization regulations have led to a positive radiative forcing over the global ocean¹³. These examples of aerosol-cloud-radiation feedback provide possibilities that MCB could be used to offset anthropogenic global warming. Various MCB protocols are hence proposed to achieve various climate mitigation targets and to test the efficiency and climate impacts of MCB perturbations using Global climate models¹⁴⁻¹⁷. One MCB modeling method used in Global climate models is to directly increase CDNC in marine low clouds¹⁸⁻²⁰ or to reduce cloud effective radius^{17,21}, which avoids many uncertainties in representing aerosol-cloud interactions in simulations²². However, sea salt aerosols influence clouds in a more complex way²³⁻²⁵ and perturbing these cloud properties ignores the direct radiative effect that the injected sea salt

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can scatter additional solar radiation back into space²⁶. The direct effect of injected sea salt has been found to be nonnegligible in the overall radiative cooling when injecting accumulation-mode or larger aerosol^{15,27}, and its contribution depends on the size of injection particles²⁸. Ahlm et al.²⁶ found that the global mean clear-sky effective radiative forcing (ERF) is as large as the corresponding all-sky ERF when injecting sea salt in median dry radius of 0.10 to 0.44 μm using three models. Mahfouz et al.¹⁵ increased sea salt emissions in dry radius of 0.1–1 μm over 30°S–30°N and found the simulated direct radiative effect of SSA predominated in the total radiative effect. Therefore, another MCB implementation strategy in model simulations is to increase sea salt emissions or concentrations, which considers both the direct and indirect effects of sea salt aerosols^{14,28}.

To better compare climate impacts of MCB among different models, the Geoengineering Model Intercomparison Project (GeoMIP), as one of the model intercomparison projects in the Coupled Model Intercomparison Project has identified standardized experiments for evaluating MCB. The latest GeoMIP includes MCB protocols including the G4cdnc (increasing CDNC of marine low cloud by 50%) and G4sea-salt (injecting SSA to offset a specific top-of-atmosphere (TOA) forcing)²⁹. However, the protocol of implementing SSA injections in extremely large ocean regions proposed in GeoMIP is relatively unrealistic and the strategies are mostly designed to mitigate the warming induced by rising greenhouse gases (GHGs) under high forcing scenarios.

The climate impacts of MCB depend on the size of the injected particles^{30–32}, seeding regions^{18,22}, background concentrations^{33,34}, and time of injection^{34,35}, which need to be investigated with specific strategies and models. Climate responses, such as global and regional temperature and precipitation, to MCB perturbations are widely discussed and many studies have suggested that MCB could effectively mitigate global warming. For example, Hirasawa et al.¹⁸ examined the climate impacts of MCB perturbation by adding 600 cm^{-3} of CDNC over the subtropical Northeast Pacific, Southeast Pacific, and Southeast Atlantic using the CESM2 model. They found that the MCB strategy produced an ERF of -1.8 W m^{-2} at TOA, cooling the surface by 1.05 K on the global average. The G4cdnc experiment from nine models in GeoMIP suggested that the temperature was reduced by -0.96 K due to a 50% increase in CDNC of marine low cloud in 2020–2069²⁰. MCB could potentially reduce the intensity of extreme events both at present and in the future³⁶. By injecting SSA over the ocean between 30°S and 30°N to offset the increasing greenhouse forcing, Aswathy et al.³⁶ reported that MCB would decrease the length of dry spells and hot days by 0.19 days yr^{-1} and 8.1 days yr^{-1} , respectively, during 2040–2069 relative to 2006–2035. However, unintended effects have been found in many MCB experiments including residual warming at high latitudes¹⁴ and anomalous hydrological circulation between land and oceans including a La Niña-like response in precipitation^{14,27}. Previous studies found that MCB would decrease the global mean precipitation, with precipitation over ocean decreasing by -0.1% to -2.35% and over land increasing by 0.01 to

1.19%^{20,37}. Müller et al.³⁸ increased the SSA between 45°S and 45°N to reduce the radiative forcing from RCP8.5 to that of the RCP4.5 scenario in the NorESM1-ME model, and found this MCB strategy was less effective at cooling the Arctic. The maximum temperature in the Arctic is lower in the MCB scenario relative to RCP8.5, but higher relative to RCP4.5, thus having an impact on the risk of wildfire. The sensitivity of climate responses to different MCB proposals indicates that the effectiveness and side effects of MCB still need further studies with diverse scenarios and models.

Carbon neutrality is one of the most practical ways to meet the Paris Agreement's target of limiting global warming to 2 °C, and even 1.5 °C, relative to the pre-industrial era³⁹. To achieve this goal, many climate policies and anthropogenic emission reduction measures must be implemented to reduce greenhouse gas concentrations that also lead to reductions in emissions of aerosols and precursors⁴⁰. Lower aerosol emissions can reduce air pollution and associated premature deaths and boost renewable energy development^{41,42}. However, the reduction in anthropogenic aerosols in a carbon-neutral scenario would weaken their cooling effect, which unmasks the warming induced by GHGs, leading to an increase in regional air temperatures⁴³. A recent study found that aerosol reduction would dominate future warming under the carbon-neutral pathway, leading to 0.5 °C–1.4 °C increases in air temperature over most terrestrial areas by 2050 relative to 2020 and causing increases in the frequency and intensity of weather extremes⁴⁴. To mitigate the aerosol reduction-induced future warming, climate intervention strategies, such as MCB, should be proposed following the carbon-neutral pathway.

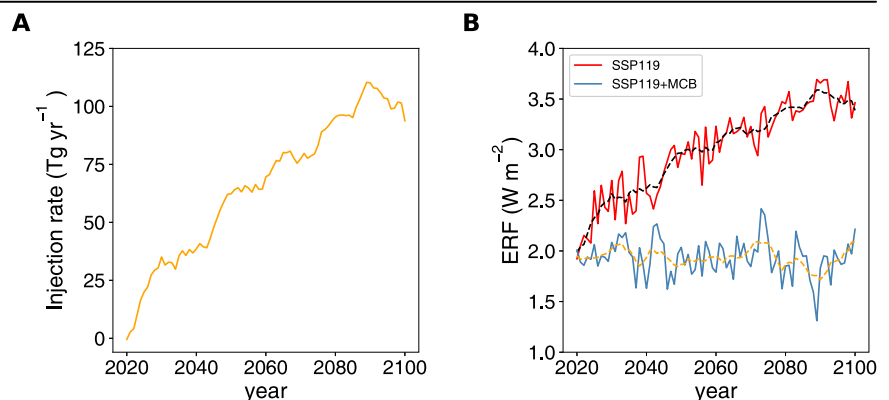
In this study we assess the impact of MCB implementation with an aerosol climate model to counter the future warming induced by the global aerosol reductions associated with the Shared Socioeconomic Pathway (SSP) 1–1.9 scenario⁴⁵, which restrains the time-varying effective radiative forcing of anthropogenic aerosols during 2020–2100 following the carbon-neutral pathway. The MCB perturbation is achieved by injecting SSA in four marine regions (North Pacific, Northeast Pacific, Southeast Pacific, and South Pacific) following Haywood et al.¹⁴ (see Methods). Most previous MCB perturbations have explored its climate impacts in reducing warming from increasing GHGs. In this study, the effectiveness and climate risks of the MCB strategy designed for mitigating future climate warming linked to decreasing anthropogenic aerosols under the carbon-neutral scenario are investigated, which could improve the understanding of implementing MCB by increasing SSA emissions in a carbon-neutral future and help develop climate mitigation strategies.

Results

Relationship between sea salt emission perturbation and ERF change

The injection amount of accumulation-mode SSA and the associated change in global mean TOA ERF in Community Earth System Model version 1.2.2 (CESM1) do not present a linear relationship within the

Fig. 1 | The needed time-varying sea salt aerosol injection rate and the modeled global mean effective radiative forcing response to aerosol reduction and marine cloud brightening. Time series of (A) total sea salt aerosol injection rate over the four oceanic areas and (B) annual global-mean effective radiative effect (ERF, W m^{-2}) changes at top-of-atmosphere during 2020–2100 from the atmosphere-only simulations with fixed sea surface temperature. The red line indicates ERF variations due to the projected changes in anthropogenic aerosols following the carbon-neutral pathway in FSSP119_AA and the blue line represents the combined effects of changes in anthropogenic aerosols and marine cloud brightening (MCB) sea salt aerosol injection in FSSP119_MCB. The dashed lines are the corresponding 7-year running average.



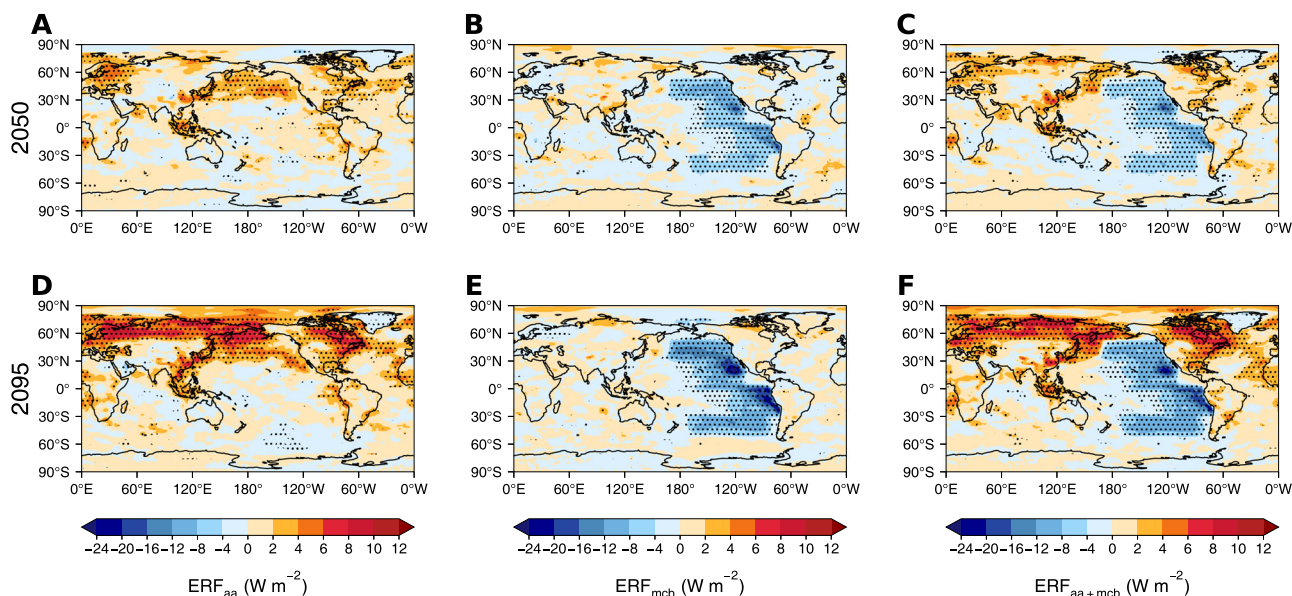


Fig. 2 | The effective radiative forcing response to anthropogenic aerosol reduction and marine cloud brightening. Spatial distributions of ERF (W m^{-2}) changes due to (A,D) the changes in anthropogenic aerosols under SSP1-1.9 scenario, (B,E) marine cloud brightening (MCB) sea salt aerosol injection, and (C,F) the combined effect of anthropogenic aerosol changes and MCB sea salt aerosol

injection from the atmosphere-only simulations. The top and bottom panels show the changes in 2050 (average of 2045–2054) and 2095 (average of 2091–2100), respectively, relative to 2025 (average of 2020–2029). The stippled areas indicate results are statistically significant at the 95% confidence level based on the Student's *t*-test.

emission perturbation range of $0\text{--}200\text{ Tg yr}^{-1}$. The radiative cooling efficiency of the MCB strategy in this study decreases with the increase in SSA injection (Supplementary Fig. 1), which has also been reported in the Hadley Center Global Environment Model version 2-Earth System (HadGEM2-ES), United Kingdom Earth System Model version 1 (UKESM1), Energy Exascale Earth System Model version 2 (E3SMv2) and CESM2^{14,22,46}. The injection rates of sea salt from 2020 to 2100 are calculated using the quadratic fitting excluding the 200 Tg yr^{-1} sample, since the required SSA emission perturbation to offset the positive ERF anomaly due to the projected anthropogenic aerosol reduction is lower than 125 Tg yr^{-1} over 2020–2100. Based on the relationship derived from CESM1 emission perturbation simulations, the SSA injection amount is approximately 93.8 Tg yr^{-1} in 2100 (Fig. 1A), equivalent to $4.57 \times 10^{-11}\text{ kg m}^{-2}\text{ s}^{-1}$ after unit conversion, in an effort to offset the 1.41 W m^{-2} of the corresponding global positive ERF anomaly from the anthropogenic aerosol reductions. Haywood et al.¹⁴ injected SSA with a dry radius of 86 nm at a rate of 413 Tg yr^{-1} over the same regions, producing a globally averaged ERF of -4 W m^{-2} . Mahfouz et al.¹⁵ injected accumulation-mode SSA at a rate of $7.66 \times 10^{-11}\text{ kg m}^{-2}\text{ s}^{-1}$ over the $30^{\circ}\text{S}\text{--}30^{\circ}\text{N}$ ocean area, resulting in a global-mean short-wave radiative forcing of -2 W m^{-2} . Comparing to the SSA injection rates and corresponding radiative flux change from many previous MCB geoengineering studies (Supplementary Table 1), the SSA emission injection amount in this study is within a reasonable range, and each unit of sea salt injection produces a stronger negative radiative effect in 2100 in this MCB strategy if simply dividing the radiative forcing of MCB by the injection level, which is related to the stronger cloud susceptibility of CESM1²² and the nonlinear relationship of MCB ERF and injection amount.

Changes in effective radiative forcing and cloud properties due to MCB

Future reductions in anthropogenic emissions of aerosols and precursors will produce a positive ERF change. By 2050, the anthropogenic aerosol reduction under the carbon-neutral pathway leads to a global mean ERF change of 0.97 W m^{-2} compared to that in 2020, and the ERF change enlarges to 1.41 W m^{-2} by the end of the 21st century (Fig. 1B), indicating the predominant role of anthropogenic aerosols on the projected warming under a pathway to carbon neutrality⁴⁴. The positive changes of ERF

induced by anthropogenic aerosol reduction are significant in the polluted mid-latitudes of the Northern Hemisphere, with positive ERF changes by $2\text{--}6\text{ W m}^{-2}$ over northern Europe, eastern China, eastern United States (U.S.) and downwind oceans in 2050 relative to the present-day state (Fig. 2A). The positive ERF changes are more pronounced in 2095, reaching 8 W m^{-2} over mid- and high latitudes of the Northern Hemisphere (Fig. 2D).

By injecting appropriate SSA in the four marine areas over the eastern Pacific Ocean, the combined ERF changes over 2020–2100 are basically steady around the 2020 level (Fig. 1B). The significant decreases of ERF due to the SSA injections are mainly centered over the injection marine areas due to the relatively short lifetime of SSA (Fig. 2B, E), with the maximum ERF change exceeding 12 W m^{-2} in 2050 and 20 W m^{-2} in 2095 relative to the present-day. The combined ERF changes due to the anthropogenic aerosol reductions and MCB SSA injection are positive over the polluted land and offshore areas and negative over the MCB implementation regions (Fig. 2C, F).

The radiative cooling via injecting SSA in the atmosphere is mainly due to a decrease in net shortwave radiative flux at TOA, both through aerosol-cloud interaction and aerosol-radiation interaction. In the last decade of the 21st century, the SSA injection results in a global mean ERF of -1.55 W m^{-2} (Supplementary Fig. 2A), with -1.48 W m^{-2} attributed to changes in shortwave radiation (Supplementary Fig. 2B). The cooling effect of MCB strategy of this study is dominated by the aerosol-cloud interactions, while the additional SSA particles also exert a minor role through aerosol-radiation interaction (Supplementary Fig. 3). Based on the ERF decomposition method proposed by Ghan⁴⁷, ERF induced by aerosol-cloud interaction (ERF_{aci}) is $-1.20\text{ (} -0.95\text{) W m}^{-2}$ and ERF attributed to aerosol-radiation interaction (ERF_{ari}) is $-0.35\text{ (} -0.19\text{) W m}^{-2}$ in 2091–2100 (2045–2054) due to the SSA injection. The dominant role of aerosol-cloud interaction is different to results of Haywood et al.¹⁴, in which the aerosol-radiation interaction was predominant at the end of the 21st century, implying a different sensitivity of radiative effect to SSA injection among models.

CDNC and liquid water path decrease over polluted land and downwind marine areas due to the anthropogenic aerosol reductions under the carbon-neutral scenario (Supplementary Figs. 4, 5). The SSA injection

Fig. 3 | Annual global mean temperature and precipitation response to anthropogenic aerosol reduction and marine cloud brightening. Time series of global annual mean (A) surface air temperature and (B) precipitation during 2020–2100 due to the changes in anthropogenic aerosols following the carbon-neutral pathway in SSP119_AA (red lines) and the combined effects of changes in anthropogenic aerosols and marine cloud brightening (MCB) sea salt aerosol injection in SSP119_MCB (blue lines). In all experiments greenhouse gas concentrations are prescribed at the 2020 level to isolate the aerosol impacts. The thick lines show the corresponding ensemble mean, the thin lines show individual ensemble members and black dashed lines show the 2020–2025 average from SSP119_MCB experiment.

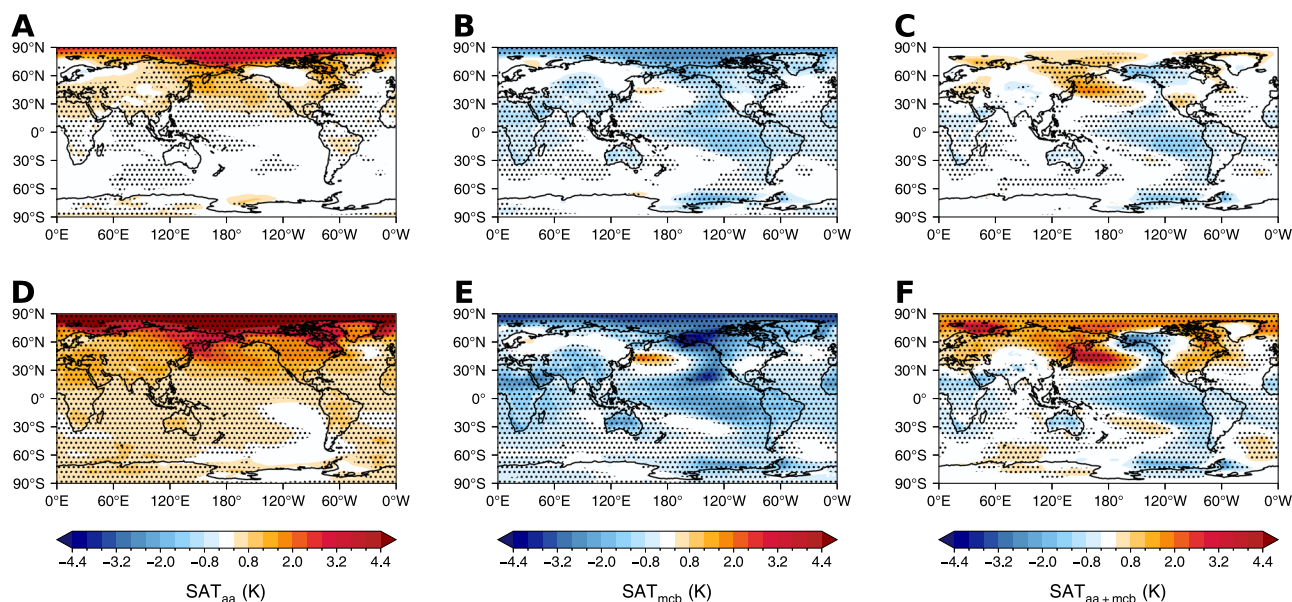
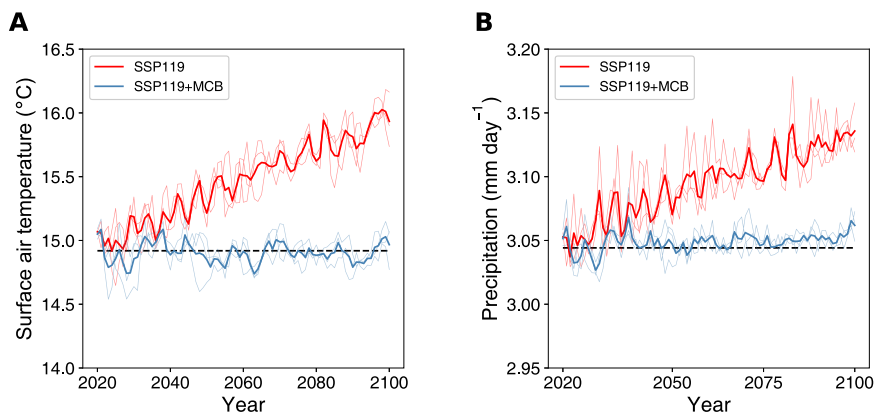


Fig. 4 | Global temperature response to anthropogenic aerosol reduction and marine cloud brightening. Spatial distribution of surface air temperature (SAT, K) changes due to (A,D) the changes in anthropogenic aerosols under SSP1-1.9 scenario, (B,E) marine cloud brightening (MCB) sea salt aerosol injection, and (C,F) the combined effect of anthropogenic aerosol changes and MCB sea salt aerosol

injection from the fully-coupled simulations. The top and bottom panels show the changes in 2050 (average of 2045–2054) and 2095 (average of 2091–2100), respectively, relative to 2025 (average of 2020–2030). The stippled areas indicate results are statistically significant at the 95% confidence level based on the Student's *t*-test.

increases the CDNC significantly over the oceanic injection regions and clouds will exhibit increased susceptibility to brightening as aerosol concentrations decline⁴⁸. Smaller cloud droplets nucleated on the injected SSA particles in the MCB strategy of this study extend the cloud lifetime, increasing low-level cloud cover (Supplementary Fig. 6), representing a desirable result of aerosol-cloud interactions that maximizes the cooling of MCB. The liquid water path and low cloud fraction also increase over some land regions, which are likely related to the atmospheric circulation adjustment to the impact of SSA injection. The cloud response to this MCB strategy also impacts the hydrological cycle, which is discussed in the next section.

Climate responses to MCB implementation to offset warming induced by anthropogenic aerosols

The cooling effect of aerosols partly masks the climate warming induced by GHGs. This masking effect will be largely weakened related to future aerosol reductions and the warming attributed to GHGs will be released again into the atmosphere. The reduction in anthropogenic aerosols leads to a steady increase in global mean surface air temperature (SAT) in the simulations,

with the global mean SAT increasing by 0.89 K in the last decade of the 21st century (Fig. 3A), revealing the pronounced GHGs-induced warming that is masked by anthropogenic aerosols. Significant warming is mostly located in continental regions, with the Northern Hemisphere experiencing stronger warming than the Southern Hemisphere, especially over high-latitude regions due to the Arctic amplification (Fig. 4A, D). China and the United States are projected to experience an SAT increase over 0.8 K by 2050. By 2100, the global mean SAT is estimated to increase by 1–2 K over land and over 4 K over the Arctic due to the projected anthropogenic aerosol reductions under the carbon-neutral scenario.

Before analyzing the results of this MCB strategy, it should be noted that the climate impacts of MCBs are different across various MCB strategies and would also depend on the models used. Adding SSA effectively restrains the global mean SAT change over 2021–2100 to the 2020 level, with the standard deviation of annual global mean SAT less than 0.08 °C, when considering both anthropogenic aerosol reductions and SSA injections (Fig. 3A). The radiative cooling generated by SSA is strong over the injection areas and expands to remote areas (Fig. 4B, E). The cooling induced by SSA injections in the eastern Pacific Ocean results in anomalous anticyclones in

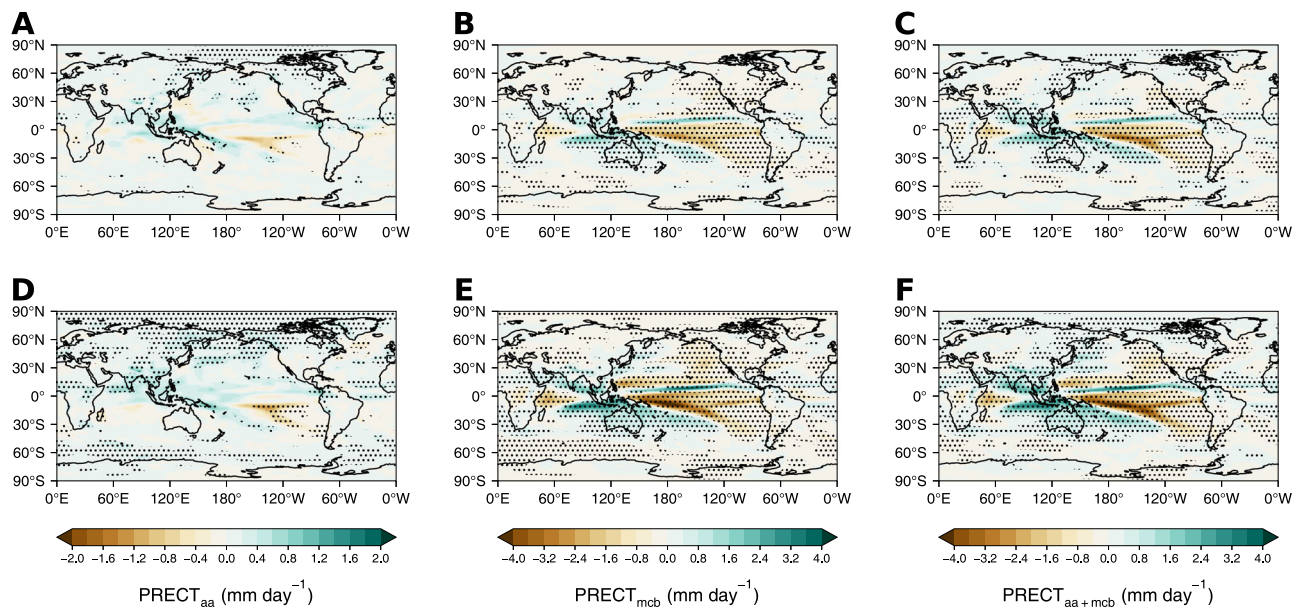


Fig. 5 | Global precipitation rate response to anthropogenic aerosol and marine cloud brightening. Spatial distribution of precipitation rate (mm day^{-1}) changes due to (A,D) the changes in anthropogenic aerosols under SSP1-1.9 scenario, (B,E) marine cloud brightening (MCB) sea salt aerosol injection, and (C,F) the combined effect of anthropogenic aerosol changes and MCB sea salt aerosol injection from the

fully-coupled simulations. The top and bottom panels show the changes in 2050 (average of 2045–2054) and 2095 (average of 2091–2100), respectively, relative to 2025 (average of 2020–2030). The stippled areas indicate results are statistically significant at the 95% confidence level based on the Student's *t*-test.

the Pacific (Supplementary Fig. 7). The anomalous easterly winds in the lower troposphere of the equatorial Pacific can strengthen the trade winds, which move cold sea surface water from the eastern tropical Pacific westward. The strengthened upwelling of cold water from the deep ocean further decreases sea surface temperature over the eastern tropical Pacific, resulting in a La Niña-like Walker Circulation pattern similar to the previous study¹⁴. In the atmosphere, the anomalous descending flows are located in the central and eastern tropical Pacific and the ascending flows are located in the western tropical Pacific and Indian Ocean due to the SSA injections (Supplementary Fig. 8), in accordance with the La Niña pattern. The anomalous high pressure over the North Pacific Ocean and Bering Sea is associated with the La Niña-like pattern (Supplementary Fig. 7). The northerly winds to the right of the anticyclone transport the cold air to 30°N, enhancing the cooling in subtropical oceans. It also reduces the temperature gradient between the mid-latitudes and the poles, weakening the northward atmospheric heat transport (Supplementary Fig. 9) and resulting in the cooling of the Arctic (Fig. 4B, E).

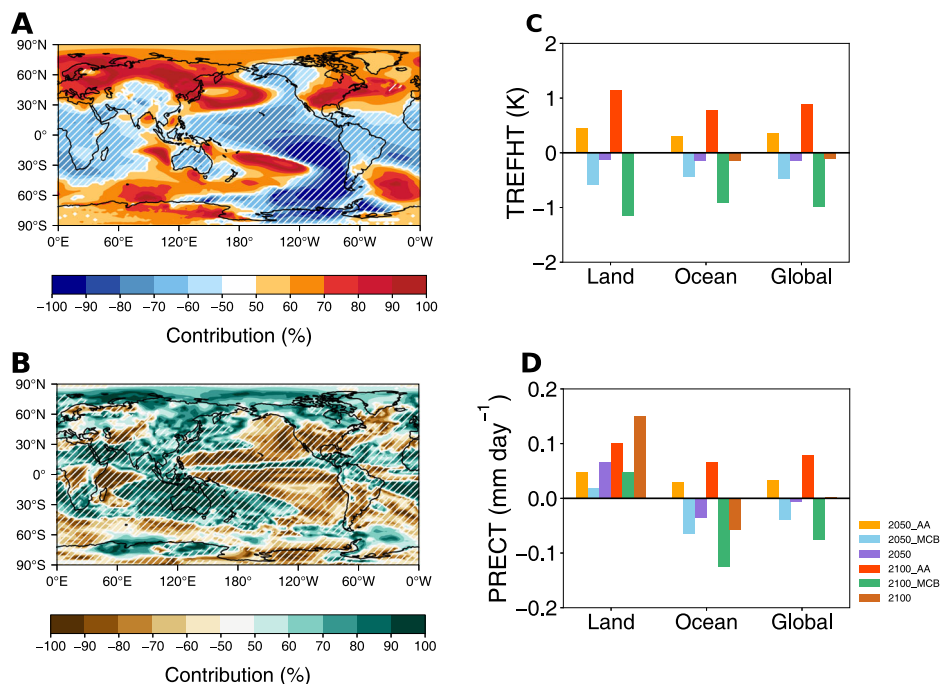
However, the unintended effects of SSA injections in this MCB strategy on regional climate are also noteworthy. The MCB implementation of this study results in a warming over the northwestern Pacific (Fig. 4B, E), resembling the La Niña sea surface temperature anomalies pattern. The SSA cooling effect does not affect the southern U.S. and Europe, even though the Northern Hemisphere SSA injection encompasses the U.S. west coast. The insignificant influences of this MCB strategy over the U.S. and Europe are related to the acceleration of the Atlantic Meridional Overturning Circulation (AMOC) (Supplementary Fig. 10). The stronger shortwave radiative effect due to SSA injections in the Northern Hemisphere (-3.2 W m^{-2} in 2095) compared to the Southern Hemisphere (-1.8 W m^{-2} in 2095) (Supplementary Fig. 11) associated with the different regional susceptibilities to MCB implementation related to background conditions (e.g., future clean air in the Northern Hemisphere) speeds up the AMOC to compensate the hemispherical asymmetric radiation gradient⁴⁹. The restoration of AMOC due to the MCB strategy in this study increases the SAT in the U.S. and Europe, weakening the cooling effect of MCB implementation. Considering both the anthropogenic aerosol reductions and SSA injection, SAT increases primarily over polluted continental regions over

northern China, Europe, the U.S. and downwind offshore oceans, while it decreases mostly over eastern Pacific oceans in the middle and end of the 21st century (Fig. 4C, F).

The global annual mean precipitation rate increases with anthropogenic aerosol reductions, by 0.08 mm day^{-1} in the last decade of the 21st century under the carbon-neutral scenario simulated by CESM1 (Fig. 3B), which is 2.6% relative to the present-day condition. The intensified precipitation is linked to the enhanced evaporation, cloud microphysics, atmospheric dynamics and thermodynamics related to the aerosol reduction-induced warming^{44,50}. Precipitation exhibits significant increases in South Asia, southern China, central and eastern Siberia, Alaska, and the tropical western Pacific, but decreases over the southeastern Pacific (Fig. 5A, D).

After the implementation of this MCB strategy, the global mean precipitation rate remains stable around the 2020 level throughout the 21st century. The stabilized global mean precipitation in our study is likely related to the fixed GHGs concentrations at 2020 level in our study. Nevertheless, according to the atmospheric energy budget⁵¹, the stabilization of global mean precipitation resulted from MCB will be easier to achieve compared with other scenarios considering the relatively small change of CO_2 concentration under the carbon-neutral scenario. The injected SSA decreases the SAT in the eastern Pacific Ocean, which enhances the Walker Circulation and produces a La Niña-like precipitation anomaly pattern that exhibits an increase around the Maritime Continent, South Asia, Southeast Asia, and Australia and a decrease of precipitation in the central and eastern tropical Pacific (Fig. 5B, E). Precipitation increase in the Sahel (Fig. 5C, F) is correlated with a warmer North Atlantic⁵² due to anthropogenic aerosol reduction and the La Niña precipitation anomaly pattern induced by SSA injections. The U.S. becomes drier due to this MCB strategy, associated with the La Niña-like poleward shift of the jet stream (Supplementary Fig. 12) that reduces moisture flux convergence across the southern U.S.⁵³. The precipitation changes due to the MCB SSA injection are much larger than those induced by anthropogenic aerosol reductions at the regional scale and the overall pattern of precipitation changes due to the combined effects (Fig. 5C, F) is similar to that due to the MCB SSA injection alone. It suggests that, although MCB can offset the increase in global mean precipitation

Fig. 6 | Contributions of anthropogenic aerosol reduction and marine cloud brightening sea salt injection to future temperature and precipitation change. Spatial distribution of major contribution to the changes in (A) surface air temperature and (B) precipitation due to anthropogenic aerosol reductions or marine cloud brightening (MCB) sea salt aerosol injection in 2095 (average of 2091–2100) relative to 2025 (average of 2020–2030) in the SSP119_MCB experiment. The white hatched lines show the areas predominantly influenced by MCB with absolute contributions larger than 50%, while the other regions are predominated by anthropogenic aerosol reduction. Contributions of anthropogenic aerosol reductions (2050_AA/2100_AA), MCB (2050_MCB/2100_MCB) and both of them (2050/2100) to changes in surface air temperature and precipitation over land, ocean, and the entire globe are shown in (C) and (D), respectively.



associated with anthropogenic aerosol reductions, it induces much stronger precipitation anomalies, especially over oceans, which are vital for the prediction of future extreme weather events.

The major contributions to projected SAT and precipitation changes in the middle and at the end of the 21st century relative to the present-day are shown in Fig. 6 and Supplementary Fig. 13, respectively, attributed to anthropogenic aerosol reductions or SSA injection in this MCB strategy. As expected, anthropogenic aerosol reduction and SSA injection have opposite effects on SAT. Anthropogenic aerosol reductions dominate SAT changes in mid- and high-latitude regions, especially over the polluted continents and their downwind oceanic regions, while SSA injections control SAT changes primarily between 30°S–30°N, particularly over oceans. Although SSA injection in this MCB strategy compensates well for the warming induced by anthropogenic aerosol reductions over both land and oceans, it does not fully mitigate the warming in the regions including Europe, the U.S., northeastern China, central and eastern Siberia and the Arctic.

The contributions to precipitation changes from the MCB SSA injection and anthropogenic aerosol reductions are more complicated. (Fig. 6D). Anthropogenic aerosol reduction enhances precipitation over both land and oceans, which is likely linked to the increase of water vapor holding capacity of the atmosphere due to the anthropogenic aerosol reduction-induced warming and aerosol-cloud interactions. It also explains the decreases in precipitation over oceans due to SSA injection. However, the SSA injection over oceans in this MCB strategy slightly enhances precipitation over land, which is related to its impact on land-ocean thermal contrast²¹. Over land, anthropogenic aerosol reduction contributes to more than 60% of the precipitation increases in East Asia, central and eastern Siberia, north-western Pacific and the Arctic. The SSA injection in this MCB implementation dominates the La Niña-like precipitation anomalies over the oceans (Fig. 6B).

Combining the specific changes in SAT and precipitation contributed by the MCB intervention in the Pacific regions and anthropogenic aerosol reductions, Sahel, India, Australia, and Amazon produce a cooler and wetter climate by the end of the 21st century than their present-day condition mainly due to the SSA injection in this MCB implementation, while the U.S. would be hotter due to anthropogenic aerosol reductions and drier as a result of the SSA injection.

The impacts of SSA injections on sea ice concentrations were also investigated (shown in Supplementary Fig. 14). The simulations suggest that anthropogenic aerosol reductions will accelerate sea ice melting in the Arctic and Antarctic and the MCB implementation would slow down, but not fully compensate for the decrease of sea ice concentration which was overwhelmed by the anthropogenic aerosol changes.

Discussion

Anthropogenic aerosols need to be substantially reduced due to climate mitigation policies to achieve carbon neutrality and clean air measures. These aerosol reductions will benefit human health but also have a warming effect across the globe, which might be mitigated by implementing MCB climate intervention strategies. In this study, a SSA injection strategy has been proposed, aiming to compensate for the change of TOA ERF of anthropogenic aerosols due to emission reductions from the 2020 level. The intervention introduces time-varying spatially uniform SSA emissions in the accumulation mode in four oceanic regions over the eastern Pacific Ocean in CESM1 model simulations during 2020–2100 to investigate the climate impacts and possible unintended effects.

Anthropogenic aerosol reductions under the carbon-neutral pathway lead to a global mean ERF change of 0.97 W m^{-2} in 2050 and 1.41 W m^{-2} by the end of the 21st century, compared to that in 2020. The SSA injection rates needed to offset the positive ERF changes are 62.28 Tg yr^{-1} in 2050 and 93.80 Tg yr^{-1} in 2100. Aerosol-cloud interaction plays a dominant role in reflecting more shortwave flux in this MCB protocol through increasing the CDNC and liquid water path due to the SSA injection. The reduction in anthropogenic aerosols is projected to increase global SAT by 0.89 K and precipitation by 0.08 mm day^{-1} in the last decade of the 21st century compared to the present-day conditions. It is worth noting that although CESM1 was reported to produce an ERF of anthropogenic aerosols in line with the multi-model averages³⁴, it has higher equilibrium climate sensitivity than multi-model simulations in CMIP6, indicating that the model likely produced strong climate responses to anthropogenic and natural aerosols⁴⁴. Nevertheless, MCB in this study effectively restrains the projected increases in global mean SAT and precipitation rate to the present-day levels.

However, the unintended effects of SSA injections in the Marine Pacific on regional climate are also noteworthy. The cooling generated by SSA particles is strong over the injection areas and expands to remote areas by

producing a La Niña-like Walker Circulation pattern and weakening the temperature gradient between the mid-latitudes and the poles. Although the overall cooling due to the SSA injections compensates well for the global warming induced by anthropogenic aerosol reductions over both land and ocean, it does not fully mitigate the warming in some regions including Europe, the U.S., northeastern China, central and eastern Siberia and the Arctic. This is partly related to the acceleration of the AMOC driven by the hemispherical asymmetric radiation gradient induced by the injections. Considering both the anthropogenic aerosol reductions and the MCB implementation, SAT increases primarily in the polluted continental regions over northern China, Europe, the U.S. and their downwind offshore areas, while it decreases mostly over eastern Pacific oceans in the middle and at the end of the 21st century. The injected SSA also produces a La Niña-like precipitation anomaly pattern that has an increase around the Maritime Continent, South Asia, Southeast Asia, and Australia and a decrease in precipitation over the central and eastern tropical Pacific. The precipitation changes due to the SSA injection in this MCB strategy are much larger than those induced by anthropogenic aerosol reductions at the regional scale. Combining the anthropogenic aerosol reductions and the corresponding MCB implementation, Sahel, India, Australia, and Amazon become colder and wetter by the end of the 21st century than the present-day mainly due to SSA injection, while the U.S. is getting hotter due to anthropogenic aerosol reductions and drier due to SSA injection in this MCB strategy.

It should be noted that the simulated climate impacts of MCB are strongly dependent on the selected seeding strategy and particular host model. This study finds that the aerosol-cloud interaction dominates the total ERF caused by the MCB implementation, while some previous studies also reported a non-negligible influence due to aerosol-radiation interaction^{14,20,27,28,37,46,55}. This is likely related to the sufficient marine low cloud cover in the injection areas in this study and the strong positive liquid water path and cloud fraction adjustments to seeding with sea salt in CESM1 model compared to other models like UKESM1 and E3SM²². Considering that there is still large uncertainty in diagnosing aerosol-cloud interactions among Global Climate Models, more improvements should be made to better evaluate the efficiency of MCB proposals. The MCB-induced La Niña temperature and precipitation anomalies in this strategy were also found in previous MCB studies that increased SSA or CDNC over low-latitude oceans^{14,18}. Wan et al.⁵⁶ implemented a regional MCB intervention over the North Pacific under present-day and mid-century condition using CESM2. They reported reduced mitigation effects of MCB on extreme heat in the western U.S. in a warming condition. Song et al.⁵⁷ used WRF-CMAQ to investigate the effectiveness of different MCB invention strategies and showed the changing trends of aerosol direct and indirect effects with injection amounts in the different ocean regions. Recently, Chen et al.⁵⁸ proposed a cloud seeding strategy over the mid-latitude oceans in winter with low susceptibility to SSA injections locally, which resulted in a more widespread cooling distributed over the globe. This indicates that MCB effectiveness is strongly dependent on the strategy and models and future MCB experiments could choose seeding areas and time more carefully to minimize the unintended effects of MCB on climate.

Though we only utilize one model here, results, such as the overcooling around injection regions and La Niña-like precipitation response similar to Haywood et al.¹⁴ and decreased global mean precipitation due to MCB SSA injection similar to the multi-model results in Stjern et al.²⁰, emphasizing the robustness of our study. Further studies are suggested to investigate the climate responses to this MCB strategy using different Global Climate Models. It is crucial that improvements about cloud microphysics parameterizations are needed to better simulating the aerosol-cloud interactions to reduce the uncertainties in the indirect radiation forcing. Moreover, understanding the mechanism of regional climate responses is essential to predict the benefits and risks of MCB strategies. Underlying mechanisms of impacts on regional climate may differ among MCB protocols. This study provides an interpretable perspective of MCB strategy for dampening the warming caused by anthropogenic aerosol reductions toward a carbon-neutral future.

Methods

Model description

The Community Earth System Model version 1.2.2 (CESM1) is used to study the climate impact of MCB. The atmospheric component of CESM1 is the Community Atmosphere Model version 5 (CAM5), which has a default resolution of 1.9° latitude by 2.5° longitude horizontally, with 30 vertical layers from the surface to 3.6 hPa. The aerosol module used here is a three-mode version of the Modal Aerosol Module (MAM3)⁵⁹, including Aitken, accumulation, and coarse modes, with a dry diameter of particles in the ranges of 0.015–0.053 μm, 0.058–0.27 μm, and 0.8–3.65 μm, respectively. MAM3 is able to simulate major aerosol species and their climate impacts, including sulfate, BC, primary organic matter, secondary organic aerosol, mineral dust, and SSA⁵⁹. To implement the MCB strategy in CESM1 by manually injecting SSA from the sea surface, the aerosol module is modified following Yang et al.⁶⁰, with SSA mass and number emissions prescribed offline using external input data.

CAM5 has several treatments of major physical processes in the atmosphere, that are particularly important to aerosol-cloud interactions⁶¹. Activation parameterization of cloud droplets from multiple aerosol modes uses a scheme developed by Abdul-Razzak and Ghan⁶². CAM5 applies a two-moment stratiform cloud microphysics scheme with a prognostic precipitation scheme to predict mass mixing ratios and number concentrations of cloud liquid and cloud ice^{63–65}. The model is capable of diagnosing the aerosol-radiation interaction (direct radiative effect) and aerosol-cloud interaction (indirect radiative effect) in stratiform cloud^{44,47,61}.

Effective radiative forcing

In this work, the effective radiative forcing (ERF) of aerosols is decomposed into two components, including the ERF induced by aerosol-radiation interaction (ERF_{ari}) and ERF induced by aerosol-cloud interaction (ERF_{aci}). The ERF, ERF_{ari} and ERF_{aci} are quantified similarly to Ghan⁴⁷, as follows:

$$\text{ERF} = \Delta F$$

$$\text{ERF}_{\text{ari}} = \Delta(F - F_{\text{clean}})$$

$$\text{ERF}_{\text{aci}} = \Delta(F_{\text{clean}} - F_{\text{clean, clear}})$$

where F is the net (shortwave and longwave) radiation flux at TOA, and F_{clean} is calculated from a diagnostic radiation call in the same simulation but neglecting the scattering and absorption of radiation by specific aerosol; $F_{\text{clean, clear}}$ is the clear-sky net radiation flux at TOA calculated from the same diagnostic call but neglecting the scattering and absorption of radiation by both specific aerosol and clouds.

Experimental design

To estimate the appropriate amount of sea salt emissions that should be injected, a series of atmosphere-only simulations with fixed sea surface temperature were performed to investigate the relationship between sea salt emissions and the corresponding ERF of the additional SSA in the CESM1 model. The efficiency of MCB depends on the size of injection particles, and previous studies have noted that SSA placed in the accumulation mode could produce more effective radiative cooling than those in the Aitken and coarse modes³⁰. Therefore, the SSA perturbation is conducted for the accumulation mode alone (0.058–0.27 μm) in this study. The perturbation is spread equally into each month. In addition to the baseline simulation with offline background sea salt emissions at the 2020 level from the CMIP6 multi-model averages, six sensitivity simulations are performed with additional 25, 50, 75, 100, 125 and 200 Tg yr⁻¹ of SSA emitted from the sea surface, uniformly distributed in each oceanic model grid of the four selected marine regions (North Pacific (30°–50°N, 170°E–120°W), Northeast Pacific (0–30°N, 150°–110°W), Southeast Pacific (0°–30°S, 110°–70°W), and South Pacific (30°–50°S, 170°–90°W), see Supplementary Fig. 1A). The four injection regions contain large amounts of marine stratocumulus cloud decks (Supplementary Fig. 1A) and are symmetrically distributed at latitudes around the equator to avoid the side effects of the asymmetric forcing on tropical precipitation¹⁴. Furthermore, the results simulated with CESM1 can be compared with those with UKESM1 using the same injection regions in Haywood et al.¹⁴ to confirm the benefits and side effects of this MCB

strategy, which helps to reduce uncertainties related to model dependency, although the undesirable regional climate impacts have been witnessed in several previous studies^{14,18,66}. Sea salt number emission is calculated based on the mass emission, the density of sea salt, and the average size of accumulation mode. The simulations are performed for 15 years using an atmosphere-only configuration. The impact of SSA perturbation on TOA radiative flux is assessed using the last 10 years of the simulations to establish the relationship between the global ERF and regional SSA emission perturbation.

The MCB strategy in this study is designed based on the SSP1-1.9 scenario, which is often used to represent the carbon-neutral pathway. The objective of MCB in this study is to restrain the time-varying global mean ERF of anthropogenic aerosols under the SSP1-1.9 scenario to the 2020 level by injecting SSA in the four selected marine areas over the eastern Pacific Ocean. First, two atmosphere-only experiments, FSSP119_AA and FSSP119_MCB, are performed to respectively assess the ERF changes due to future reductions in anthropogenic aerosols and the combined effect of anthropogenic aerosol reduction and MCB perturbation on ERF. The two simulations are prescribed with the background SSA emissions at the 2020 level except that the FSSP119_MCB has additional SSA injections in certain amounts every year from 2020 to 2100. To quantify the aerosol impacts, anthropogenic emissions of aerosols and precursors follow the SSP1-1.9 scenario in the two simulations, while greenhouse gas concentrations are prescribed at the 2020 level. The SSA injection rates during 2020–2100 in FSSP119_MCB are calculated every year according to the 7-year running average of future changes in ERF of anthropogenic aerosols relative to 2020 in FSSP119_AA, based on the relationship between SSA emission and ERF of SSA obtained from the emission perturbation simulations. To examine the climate influences, two fully-coupled experiments (SSP119_AA/SSP119_MCB) are performed to investigate the effectiveness and side effects of MCB perturbation, with configurations kept the same as FSSP119_AA/FSSP119_MCB except that the ocean model is dynamically coupled with the atmosphere model. Three ensemble members with different initial conditions are included in the coupled MCB experiments. The experimental design is summarized in Supplementary Table 2.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Our code and results can be found at <https://doi.org/10.5281/zenodo.16560314>.

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Author contributions

Y. Yang designed the research. Y. Yu performed simulations, analyzed the data and wrote the original draft. H.W., L.M.R., P.W., J.J., J.C., Y.Y., W.X., and H.L. discussed the results and reviewing the paper.

Competing interests

The authors declare no competing interests.

Additional information

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