Unexpected failure of regional marine cloud brightening in a warmer world

Katharine Ricke
kricke@ucsd.edu

University of California San Diego  https://orcid.org/0000-0002-2780-7213

Jessica Wan
University of California San Diego  https://orcid.org/0000-0003-3757-6436

Chih-Chieh (Jack) Chen
National Center for Atmospheric Research

Simone Tilmes
National Center for Atmospheric Research

Matthew Luongo
University of California San Diego  https://orcid.org/0000-0002-2996-7579

Jadwiga Richter
National Center for Atmospheric Research  https://orcid.org/0000-0001-7048-0781

Keywords:

Posted Date: September 12th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3250111/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License. Read Full License

Additional Declarations: There is NO Competing Interest.

Version of Record: A version of this preprint was published at Nature Climate Change on June 21st, 2024. See the published version at https://doi.org/10.1038/s41558-024-02046-7.
Title: Unexpected failure of regional marine cloud brightening in a warmer world

Authors: Jessica S. Wan¹, Chih-Chieh-Jack Chen², Simone Tilmes³, Matthew T. Luongo¹, Jadwiga H. Richter², Katharine Ricke¹,⁴*

Affiliations:

¹Scripps Institution of Oceanography, University of California San Diego; La Jolla, CA, USA.
²Climate and Global Dynamics Laboratory, National Center for Atmospheric Research; Boulder, CO, USA.
³Atmospheric Chemistry, Observations, and Modeling Laboratory, National Center for Atmospheric Research; Boulder, CO, USA.
⁴School of Global Policy and Strategy, University of California San Diego; La Jolla, CA, USA.

*Corresponding author. Email: kricke@ucsd.edu

Abstract: Marine cloud brightening is a solar geoengineering¹³ proposal to cool atmospheric temperatures and reduce some impacts of climate change. To-date, modeling studies of solar geoengineering have primarily focused on large-scale schemes with objectives of stabilizing or mediating changes in global mean temperature⁴⁷. However, these global proposals pose substantial governance challenges⁸¹⁰, making regional interventions tailored toward targeted climate outcomes potentially more attractive in the near-term. In this study, we investigate the efficacy of regional marine cloud brightening in the North Pacific designed to mitigate extreme heat in the Western United States. We find cloud brightening in a remote mid-latitude region cools our target region more than brightening in a proximate subtropical region, but both schemes reduce the relative risk of dangerous summer heat exposure under present-day conditions, by 39% and 25% respectively. However, the same cloud brightening interventions under mid-century warming produce significantly hotter rather than cooler summers, both in the Western U.S. and other areas of the world. We trace this loss of efficacy to a nonlinear response of the Atlantic Meridional Overturning Circulation to the combination of greenhouse gas driven warming and regional cloud brightening. Our result demonstrates a risk in assuming that regional interventions that are effective under certain conditions will remain effective as the climate continues to change.
Main Text:

Despite progress in mitigation efforts, the pathways to remaining under the 1.5 to 2.0°C global mean temperature limits set by the Paris Climate Agreement are becoming increasingly narrow\textsuperscript{11}. The most plausible pathways to achieving these goals will likely have to rely on some combination of greenhouse gas emissions reductions, carbon dioxide removal, and solar geoengineering (SG), which refers to activities that deliberately cool the planet by increasing the amount of sunlight reflected to space\textsuperscript{1}.

Most SG studies have simulated the outcomes of global-scale interventions to achieve a physical objective such as stabilization of global surface temperature\textsuperscript{4,5} or precipitation\textsuperscript{12,13}. However, given the extensively documented governance challenges associated with coordinated global climate risk management\textsuperscript{8–10}, large-scale schemes may be sociopolitically unfeasible, raising the question of what would happen if SG were deployed for regional climate risk instead. Indeed, the Australian government has funded a cloud brightening experiment to understand its potential application to protect the Great Barrier Reef\textsuperscript{14}. Whether an effective regional deployment of SG is physically or technically feasible is largely unknown, but the few studies conducted indicate climate responses from a local intervention large enough to substantially alter regional climate are unlikely to be confined to the target region\textsuperscript{15–18}.

Marine cloud brightening (MCB) is a SG strategy that is particularly amenable to regional applications since it would be deployed in the lower troposphere over a relatively small area. The goal of MCB is to cool parts of the Earth by seeding the lower atmosphere with sea salt particles to form brighter marine stratocumulus clouds\textsuperscript{2,3}, a phenomenon that has been observed in the paths of large shipping vessels seeded by sulfate particles from ship exhaust. While most modeling studies have explored the effects of cloud brightening in idealized simulations to achieve a global climate response\textsuperscript{19–22}, MCB could theoretically be leveraged in a regional implementation\textsuperscript{14} to achieve a sociopolitical or physical objective.

Targeted marine cloud brightening to reduce heat risk in the Western United States

In recent years, the Western United States has experienced record-breaking summer heatwaves\textsuperscript{23}. If localized cooling induced by MCB were feasible, the Western U.S. could potentially be a candidate region to benefit from such an intervention. We use a state-of-the-art, fully coupled Earth system model (ESM), the Community Earth System Model version 2 (CESM2)\textsuperscript{24}, with a novel MCB parameterization, to explore the outcomes of regionally focused MCB in the North Pacific to mitigate extreme heat over the Western U.S. under 2010 and 2050 conditions (see ‘Marine Cloud Brightening Modeling Experiments (CESM2)’, in Methods). We simulate two MCB strategies to mitigate Western U.S. climate extremes: i) subtropical cloud brightening off the coast of California which is geographically near the target region and which prior studies have identified as susceptible to brightening\textsuperscript{19,20,25} and ii) a novel mid-latitude deployment near the Aleutian Islands as a remote response to the Western U.S. Both seeding regions are equal in area (2% of the global ocean), and in each, we nudge the cloud droplet number concentration to a constant of 500 particles/cm\textsuperscript{3} from March through November. We use this strategy rather than prescribing a fixed radiative forcing to better compare MCB efficacy for equivalent deployment effort.

Previous MCB modeling\textsuperscript{19,20} and ship-track studies\textsuperscript{26} suggest the Northeast Subtropical Pacific (NESP) stratocumulus cloud deck is a location proximate to the target region with high
susceptibility to brightening. There is a high fraction of low cloud cover over the NESP in both the historical satellite record (Fig. 1a) and the large ensemble mean (Fig. 1b) of the ESM used in this study. Beyond physical brightening susceptibility, we postulate there might be certain economic advantages to deploying MCB geographically closer to shore by leveraging existing shipping routes, though cost estimates of MCB are not well quantified.

Fig. 1. Comparison of observed and model low cloud fraction and the modeled temperature response from two marine cloud brightening schemes. a, Mean 1984-2009 observed low cloud fraction from March to November from the International Satellite Cloud Climatology Project (ISCCP) (see ‘International Satellite Cloud Climatology Project (ISCCP) dataset’ in Methods). The magenta (mid-latitude) and green (subtropical) contours show the average cloud brightening regions from March to November (includes grid cells brightened in at least half of the seeding months). The black contour shows the Western U.S. target region. b, 1984-2009 ensemble mean low cloud fraction from March to November from the CESM2 Large Ensemble (LENS2) ensemble mean. c, d, Annual change in surface temperature and mean wind vectors (control) for mid-latitude (c) and subtropical (d) MCB under 2010 conditions. All plots show only grid cells with p ≤ 0.05 from a two-sided t-test.

Observations and modeled historical climatology also indicate an elevated low cloud fraction and high ship track density over the mid-latitude North Pacific (Fig. 1a,b), yet this region has not been considered in MCB modeling studies to-date. While observations and models have different absolute magnitudes of cloud cover, they generally agree on which seasons and regions have the highest low cloud cover throughout the Pacific. Extratropical perturbations can efficiently trigger tropical responses via atmospheric feedbacks and lead to amplified cooling, which has been demonstrated in idealized modeling studies in the Northern Hemisphere and in case studies between the extratropical Southern Hemisphere and tropical Pacific. Prevailing climatological winds can advect extratropical temperature anomalies equatorward, triggering a series of subtropical and tropical feedbacks that amplify cooling throughout the Pacific. We test a hypothesis that mid-latitude MCB near the Aleutian
Islands could tap into a similar mechanism in the Northern Hemisphere to produce a strong cooling effect over the Western U.S.

**Efficacy of global and regional cooling from marine cloud brightening**

We simulate the outcomes of our two seasonal MCB interventions (magenta and green contours in Fig. 1) under cyclical 2010 and 2050 conditions relative to unperturbed control simulations (see ‘Marine Cloud Brightening Modeling Experiments (CESM2)’, in Methods). We find that under 2010 conditions, mid-latitude MCB produces a larger global mean cooling response (-0.52 ± 0.29°C; Fig. 1c) than subtropical MCB (-0.27 ± 0.35 °C; Fig. 1d) by almost a factor of two, though the subtropical strategy produces a slightly larger temperature response per unit forcing (subtropical MCB: 0.51 ± 0.33 °C/W/m²; mid-latitude MCB: 0.44 ± 0.27 °C/W/m²). Mid-latitude MCB produces a larger negative net top-of-atmosphere radiative forcing downstream of the MCB patch (Extended Data Fig. 1c) and more widespread cooling outside of the cloud brightening region (Extended Data Fig. 1d).

Similar to previous findings, the initiating mechanism of this teleconnection between the mid-latitude North Pacific and the tropics is mean wind advection (Fig. 1c, d). In the first two years of mid-latitude MCB, the cooling is mostly confined to the seeding region before spreading to the coast of the Western U.S. and the equatorial Pacific in subsequent years (Extended Data Fig. 2a,c). The movement of the cold patch follows the mean-state anticyclonic North Pacific High southward before merging with the easterly trade winds, creating a high sea level pressure (SLP) anomaly in the NESP extending across the equator (Extended Data Fig. 2b,d). Cooling in subsequent years is sustained by high SLP (due to Rossby wave teleconnections) which strengthens the trade winds (Extended Data Fig. 2e-h) and amplifies cooling over the ocean, likely via a combination of the Wind-Evaporation-Sea surface temperature feedback and low-cloud feedback. Similar dynamics (summarized in Extended Data Fig. 3) occur under subtropical MCB (Extended Data Fig. 4), but because the absolute radiative cooling is smaller, the additional cooling from the feedback is less than in the mid-latitude case.

To quantify MCB’s reduction of summer heat extremes over our target region, the Western U.S., we calculate bias-corrected apparent temperature (AP) (see ‘Apparent Temperature’ and ‘Bias Correction (ERA5)’ in Methods), which has been used to characterize human impacts under other SG interventions. The United States National Weather Service defines a set of thresholds that link AP to the physiological effects of exposure. We find MCB interventions under 2010 conditions substantially reduce regional exposure to the most severe summer heat, particularly in the mid-latitude case, as hypothesized above. For example, exposure to heat beyond the danger threshold is reduced from 119 million people-days per summer without MCB to 72 million in the mid-latitude case and 89 million in the subtropical case (Supplementary Table 1), amounting to reductions in relative risk of 39% and 25% respectively (Fig. 2a; Supplementary Table 2).
Despite inducing substantial regional cooling under 2010 conditions, our MCB interventions under 2050 conditions are relatively ineffective at reducing extreme heat exposure, and even counterproductive for some heat thresholds and locations. While some coastal regions in the Pacific Northwest experience a reduction in extreme heat exposure, particularly under mid-latitude MCB (Fig. 2f), there are notable increases in extreme heat exposure farther inland and throughout California (Fig. 2f,g) that counteract coastal cooling when averaging across the Western U.S. As temperatures rise, MCB, like other SG proposals, may be more seriously considered for climate risk management. However, the results suggest that MCB interventions could become less effective under mid-century warming.

**Far-reaching side effects of regional MCB**

MCB also triggers unexpected climate responses in remote regions in 2010 and 2050. Under 2010 conditions, mid-latitude and subtropical MCB induce substantial, nearly ubiquitous cooling over land and considerable precipitation responses, including a drying of the Sahel and the Western U.S. target region (Fig. 3a,b; Extended Data Fig. 5a,b). However, under 2050 conditions, certain regions, including northeast Asia, Europe, and central North America, experience hotter summers with MCB than would otherwise occur under global warming (Fig. 3c; Extended Data Fig. 5c). Europe suffers warmer summers under both MCB strategies.
despite experiencing relative cooling similar to the Western U.S. in 2010 (Fig. 3a; Extended Data Fig. 5a). These large remote temperature increases indicate MCB triggers a substantial nonlinear response within the climate system.

![Fig. 3. Present and future responses in summer apparent temperature and annual mean precipitation under mid-latitude MCB. a, Change in bias corrected summer (JJA) apparent temperature [see ‘Apparent Temperature’ in Methods, eq. 1] and (b) annual mean precipitation under 2010 mid-latitude MCB compared to no MCB. c, the same as (a) and (d) the same as (b) except for the responses under 2050 conditions. Ocean and insignificant (p>0.05) values are masked out.](image)

This shift in the dynamic response of the climate system to North Pacific MCB appears to be linked to the Atlantic Meridional Overturning Circulation (AMOC) response to climate change. In CESM2, the AMOC is significantly weaker under 2050 conditions (~67%; p<0.05) relative to 2010 conditions (Fig. 4b; Extended Data Figs. 6c and 7c). Zonal-mean energy transport theory suggests that the AMOC will spin-up and then transport more heat northward to smooth the interhemispheric energy gradient created by either of our MCB cooling strategies. We find mid-latitude MCB substantially accelerates the AMOC in 2050 (+6.4 Sv; Fig. 4) while in 2010, the AMOC response to the same MCB perturbation is much smaller (+1.7 Sv; Fig. 4b; Extended Data Fig. 6a), though both responses are statistically significant (p<0.05). The larger 2050 AMOC response relative to 2010 suggests that the weakened 2050 AMOC may be easier to perturb via energetic forcing, MCB or otherwise. This substantial 2050 AMOC spin-up leads to increased northward heat transport (Extended Data Fig. 8), which corresponds to an increase in surface heat flux over the North Atlantic and warming over...
Europe (Extended Data Fig. 9). The resultant pattern in apparent temperature anomalies (Fig. 3c), including significant warming rather than cooling over the target region, is characteristic of the stationary Rossby waves associated with other phenomena associated with heterogeneous mid-latitude surface heat flux anomalies\(^{37,38}\).

**Fig. 4. Nonlinear Atlantic Meridional Overturning Circulation (AMOC) response to MCB.**

a, Change in AMOC to mid-latitude MCB under 2050 conditions. The x-axis shows the latitude of the zonal mean, the y-axis shows depth from the sea surface, and the shading shows the AMOC strength in Sverdrups (Sv). 30-year difference from monthly mean output is plotted.

b, Mean AMOC strength at a reference point (Lat: 35 °N; Depth: 1000 m; denoted by the star in (a)) under 2010 and 2050 conditions for no MCB, mid-latitude MCB, and subtropical MCB. The 30-year period for the 2050 cases and 2010 No MCB case is years 56-85 and the 30-year period for the 2010 MCB cases is years 21-50 due to missing data for the 2010 control case. However, the AMOC is in apparent equilibrium for all cases despite the differences in the time periods used for the analysis, suggesting that the discrepancy is not significantly influencing the results. Error bars show two standard deviations for the monthly output from each simulation over the 30-year analysis period.

Another factor contributing to the reduced efficacy of our MCB strategies under 2050 conditions compared to 2010 may be circulation changes associated with a warming planet in CESM2. By 2050, circulation in the North Pacific becomes more cyclonic (Supplementary Fig. 1)\(^{39}\) such that the dynamical mechanism is now operating under background conditions with slower (or even reversed) winds in the North Pacific (Supplementary Fig. 2). Low cloud cover in the North Pacific also diminishes (Extended Data Fig. 10), suggesting that a larger area for cloud seeding may be needed to achieve a similar cooling response to that achieved under 2010 conditions. However, changes in winds or cloud cover alone would only reduce the cooling response to MCB, not induce remote warming, making the nonlinear AMOC response a more plausible explanation for the North Atlantic warming.

**Outlook for regional geoengineering in a changing climate**

In this study, we demonstrate the potential for marine cloud brightening to trigger a climate teleconnection for regional climate impacts reduction. As climate change becomes more disruptive, countries may be motivated to pursue targeted schemes conducted within their own
sphere of influence (e.g., Australia’s Reef Restoration and Adaptation Program\(^{40}\)). Because global SG schemes present substantial, well-documented governance challenges\(^{8-10}\), regional geoengineering may present a more politically feasible pathway to implementation of SG proposals. However, the effects of regional schemes—which have been little researched to-date—may prove much more difficult to predict than global ones because concentrated, rather than diffuse, forcings are more likely to trigger nonlinear climate responses.

Unintended side effects of SG remain one of the strongest concerns about any future deployment, regional or otherwise. We demonstrate that by implementing MCB in regions of the northeast Pacific that have been identified as particularly susceptible to cloud brightening it is possible to alleviate summer extreme heat exposure in the Western United States under certain climate conditions, but these risk reductions come with unintended side effects both within and outside of the target region. While this is just one exploration of uncertainty associated with regional geoengineering, the results illustrate that the timing and location of the intervention strongly influences the distribution of benefits and harms. Our study underscores the danger in assuming that geoengineering schemes that are effective under certain climate conditions will remain effective as the climate continues to change.

Our results are produced using a single cloud parameterization in one ESM, and thus subject to the biases and uncertainties typical of all such models. While the model and observations agree on which regions of the North Pacific have elevated low cloud fraction, CESM2 simulates a higher low cloud cover in mid-latitudes, which could mean we are overestimating the brightening susceptibility of the mid-latitude region relative to that of the subtropics. As additional work on this topic identifies other feasible or attractive regional options, those cases would benefit from simulation under alternative parameterizations, potentially derived from cloud-resolving or large-eddy simulations, and additional global climate modeling. We also model MCB by simply increasing cloud droplet number concentration, rather than injecting any aerosols. Prior studies show that the direct radiative effect of sea salt aerosols contributes non-negligible cooling\(^{41,42}\), which would lead to an underestimation of cooling from mid-latitude MCB in our study. Other ESMs also have different mean-state AMOCs and AMOC sensitivities to forcing which would likely lead to different outcomes. None of these caveats alter the core conclusion of the study that substantial nonlinear climate system responses may result from regional geoengineering activities.

To our knowledge, our study is the first to demonstrate the efficacy of targeted, regional marine cloud brightening to mitigate extreme heat exposure over a remote land region through manipulation of upstream dynamics and a resultant climate teleconnection. An examination of the complex mechanisms that make this remote intervention effective at regional cooling under present-day conditions, but ineffective under warmer mid-century conditions, illustrates the challenges scientists and decision makers will face if climate risk management proposals such as MCB remain largely ungoverned, as they are today. The global SG schemes focused on in the literature to-date may understate the extent to which future MCB deployment could trigger nonlinear responses in the climate system. Regional interventions that appear promising for climate risk management under present-day conditions may not remain effective in a warmer world.
Main References


Methods:

Marine Cloud Brightening Modeling Experiments (CESM2)

To model our two MCB strategies, we first assess which regions have high brightening potential in the model by analyzing 10 years (2000-2009) of monthly cloud liquid water path (LWP; proxy for low clouds) output from 40 ensemble members of the Community Earth System Model version 2 (CESM2) Large Ensemble (LENS2) with smoothed biomass burning emissions. For each climatological month, we rank the grid cells with the highest LWP in the subtropical (Lat: 15°N to 40°N; Lon: 145°W to 112°W; Supplementary Fig. 3) and mid-latitude (Lat: 40°N to 60°N; Lon: 140°E to 112°W; Supplementary Fig. 4) North Pacific, each up to a 2% global ocean area threshold to develop MCB ocean seeding masks.

We simulate MCB in CESM2 by setting the cloud droplet number concentration (CDNC) tendency in the lower boundary layer (p>850 hPa) for the ranked grid cells to a constant of 500 particles/cm³ (annual mean CDNC from the 2010 control in both seeding regions is on the order of 40 particles/cm³). This simplified representation of MCB bypasses the addition of sea salt aerosols and hence the large uncertainty with aerosol-cloud-interactions in global climate models. This approach allows us to focus on the climate responses to MCB by perturbing the model in the next step of the causal chain (inject aerosols → aerosolize and activate into CCN → increase CDNC → enhance cloud reflectivity). We note that the direct radiative effect of sea salt aerosols has been found to contribute a non-negligible cooling, so the results from our study likely underestimate the total radiative effect of MCB. We also only apply MCB in March through November when MCB would be most effective due to higher Northern Hemisphere solar insolation. While the change in average CDNC and radiative forcing is different between the two MCB strategies, we argue this is the best approach to compare MCB efficacy and applicability because it represents a strategy of equivalent effort level (e.g., same resources deployed in different regions).

Finally, we use the fully-coupled CESM2 version 2.2 to assess the climate outcomes of MCB. We run one control (no MCB) and two MCB (subtropical and mid-latitude) simulations using the ocean seeding masks under “2010 conditions” (2006-2014 mean cyclical emissions) and “2050 conditions under SSP2-4.5” (2045-2054 mean cyclical emissions) (Supplementary Table 3). By running cyclical simulations, we remove the transient effects of changing background emissions which allows us to better isolate the climate responses to MCB alone. We run the 2010 simulations for 50 years and the 2050 simulations for 85 years, using the last 30 years of each simulation for analysis. We allow a longer spin up time for the 2050 simulations since we impose MCB on top of a more imbalanced state due to stronger future anthropogenic forcing. Running the model to true steady state can take ~1000s of years due to deep ocean adjustment, so given computational resource limitation, we ran our simulations long enough for the global mean temperature time series to begin stabilizing (Supplementary Fig. 5).

International Satellite Cloud Climatology Project (ISCCP) dataset

We use monthly satellite data between 1984 to 2009 from the basic ISCCP H-Series to compare observed low cloud fraction to the modeled cloud fraction in CESM2 LENS2. ISCCP is one of the longest, continuous cloud data records available and is frequently used to understand the long-term relationship between climate and clouds. We calculate low cloud fraction in ISCCP as the sum of
cloud amount for the six cloud types below 680 hPa (liquid cumulus, liquid stratocumulus, liquid stratus, ice cumulus, ice stratocumulus, ice stratus).

Apparent Temperature

Apparent temperature (AP) is a metric of thermal discomfort commonly used to study extreme temperature impacts on human health\(^\text{44-46}\) and more recently in the SG literature to understand how solar geoengineering might alleviate urban heat exposure\(^\text{34}\). We adopt the formula proposed in Steadman (1984):

\[
AP = -2.7 + 1.04 \times T_{z=2m} + 2 \times e - 0.65 \times U_{z=10m}
\]

where \(AP\) is the apparent temperature (°C), \(T_{z=2m}\) is the 2-m air temperature (°C), \(e\) is the vapor pressure (kPa), and \(U_{z=10m}\) is the 10-m wind speed (m/s). \(e\) is calculated as:

\[
e = e_s \times RH
\]

\[
e_s = \begin{cases} 
0.61078 \times \exp \left( \frac{17.2693882 \times T_{z=2m}}{T_{z=2m} + 237.3} \right), & T_{z=2m} \geq 0 \\
0.61078 \times \exp \left( \frac{21.8745584 \times (T_{z=2m} - 3)}{T_{z=2m} + 265.5} \right), & T_{z=2m} < 0
\end{cases}
\]

where \(e_s\) is the saturation vapor pressure (kPa) calculated using the Clausius-Clapeyron equation and \(RH\) is the relative humidity (%).

One of the strengths of using AP is that it can be easily translated into a heat index or risk of exposure. The United States National Weather Service (NWS) defines a set of heat index thresholds\(^\text{35}\) that qualitatively classify the physiological effects a person might experience with prolonged exposure. For example, an apparent temperature of 39 °C indicates “extreme caution” of possible heat-related health outcomes including heat stroke, cramps, or exhaustion\(^\text{35}\). These heat index classifications are the same ones used when the NWS issues excessive heat warnings, making the metric ubiquitous in both environmental health research and public weather broadcasts. While AP can be calculated across any time scale, we present daily maximum summer (JJA) apparent temperatures over the Western U.S. which uses daily model output for each variable and daily maximum 2-m air temperature for \(T_{z=2m}\). We note that while AP allows us to easily compare against existing human health thresholds, the metric resembles the spatial distribution and relative magnitude of surface air temperature and thus leads to no substantial qualitative changes than using standard temperature (Supplementary Fig. 6).

Bias Correction (ERA5)

In the climate modeling literature, it is generally acceptable to directly compare model output from two simulations if we are interested primarily in the difference in variables between cases. However, when calculating threshold-based metrics of heat exposure like apparent temperature where the absolute magnitude of the modeled output matters, we must account for potential model biases.
We correct the modeled inputs to calculate AP ($T_{z=2m}, e_s, U_{z=10m}, RH$) using the European Centre for Medium-Range Weather Forecasts’ (ECMWF) fifth generation of global climate and weather reanalysis (ERA5)\textsuperscript{47,48}. ERA5 is one of the highest resolution global coverage products available and represents the variables used in our analysis particularly well\textsuperscript{49} compared to weather station observations and other reanalysis products, so we choose this product for our bias correction. We use monthly averaged data from 2005 to 2014 on the 0.25° x 0.25° atmospheric horizontal grid for all variables except maximum reference height air temperature, which is only available at the daily timestep. The reanalysis is regridded to the default CESM2 0.9° x 1.25° horizontal grid before converting units.

To bias correct AP, we first compute the monthly climatology of each reanalysis variable over the 10-year period (same period as the cyclical emissions for the 2010 control case). For each climatological month, we then subtract the ERA5 mean from the 2010 control modeled mean to obtain the present-day model bias, which is then subtracted from all monthly and daily modeled output matched to the corresponding month. The bias corrected model output is then used to compute daily maximum apparent temperature (Supplementary Fig. 7). In essence, this bias correction method removes biases in the modeled seasonal cycle and forces the 2010 control simulation to agree with the reanalysis over the same cyclical emissions period (2005 to 2014). Internal model biases that exist in this time period are assumed to remain constant when MCB is applied and under future conditions.

Population Data and Weighting

All gridded population data used in the analysis is obtained from the Socioeconomic Data and Applications Center (SEDAC). We use the Gridded Population of the World version 4 (GPWv4) product\textsuperscript{50} for 2010 population estimates and the SSP2 global 1-km downscaled total population v1.01\textsuperscript{51} for 2050 population estimates under SSP2-4.5. Population count data is first converted to population density in each grid cell before bilinearly interpolating to the CESM2 0.9° x 1.25° horizontal grid and converting back to population count.

We use the 2010 population to weight the modeled 2010 AP and 2050 population under SSP2 to weight the 2050 AP. However, we also conducted the weighting using the same 2010 population to weight AP in both time periods and found minimal changes (Supplementary Fig. 8). This suggests that changes in exposure to extreme temperatures to MCB between the two time periods are primarily due to the climate conditions and not changes in the magnitude or distribution of projected population.

Methods references:


**Acknowledgments:** This work resulted from support from the National Center for Atmospheric Research Early Career Faculty Innovator Program Cooperative Agreement Number 1755088. This work was supported by the National Center for Atmospheric Research (NCAR) which is a major facility sponsored by the National Science Foundation (NSF) under Cooperative Agreement No. 1852977. The CESM project is supported primarily by NSF. We would like to acknowledge the high-performance computing support from Cheyenne (doi:10.5065/D6RX99HX) provided by NCAR’s Computational Information Systems Laboratory, sponsored by NSF (project numbers UCOR0057 and UCSD0040). JSW acknowledges the support of the National Defense Science and Engineering Graduate Fellowship Program. MTL acknowledges the support of National Aeronautics and Space Association Future Investigators in NASA Earth and Space Science and Technology Fellowship 80NSSC22K1528. We also acknowledge the CESM2 Large Ensemble Community Project and supercomputing resources provided by the IBS Center for Climate Physics in South Korea. Hersbach et al., (2023) was downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store (2023). We thank John Moore for guidance on calculating apparent temperature and Pascal Polonik, Duncan Watson-Parris, and Shang-Ping Xie for helpful discussions.

**Contributions:** JSW and KR conceived of the study. JSW, CCC, ST, JHR and KR designed the experiments and developed the methodology. CCC developed the CESM source code modifications. JSW and ST ran the simulations. JSW, ST and MTL analyzed the output. JSW and KR developed the visualizations of the results. JSW wrote the original draft of the manuscript and all co-authors contributed to review and editing.

**Competing interests:** Authors declare that they have no competing interests.

**Data and materials availability:** All data, code, and materials used in the analysis will be made available at https://doi.org/10.6075/J0HQ4036 following submission of this manuscript.
Extended Data Fig. 1. Summary of 2010 response to MCB. Change in 2010 cloud droplet number concentration at the nearest pressure level (~857 hPa) to boundary layer height (a, e), low cloud cover (b, f), net top-of-atmosphere radiative forcing (c, g), and reference height air temperature (d, h) to mid-latitude (a-d) and subtropical (e-h) MCB. The mean cloud brightening region is denoted by the magenta and green contours for mid-latitude (a-d) and subtropical (e-h) MCB, respectively. Values shown are within 95% confidence from a two-sided t-test on related samples and the top right value is the area-weighted annual global mean anomaly. Averages over the last 30 years of the simulation.
Extended Data Fig. 2. 2010 transient surface temperature and pressure response to mid-latitude MCB. 2010 mid-latitude MCB annual mean changes in reference height air temperature overlaid with changes in near-surface winds (~993 hPa; arrows) (a, c, e, g) and sea level pressure (b, d, f, h) for the first 4 years of the simulation.
Extended Data Fig. 3. Schematic of the key physical processes driving the North Pacific mid-latitude MCB teleconnection under 2010 conditions. The schematic diagram begins with (0) the marine cloud brightening perturbation in the mid-latitude region causing a negative temperature anomaly within the seeding region. Then (1) mean wind in the North Pacific High advects the cool temperatures southward along the coast of North America, which develops (2) a high sea-level pressure anomaly. Increased SLP in this region (3) strengthens the trade winds which amplifies cooling throughout the subtropical Pacific basin through evaporative cooling. Perturbed trade winds alter equatorial convective processes, strengthening the Northern Hemisphere Hadley cell and shifting the Intertropical Convergence Zone southward (not shown). (4) Increased subtropical subsidence, further strengthens the high SLP anomaly and increases lower troposphere stability which is conducive toward surface cooling and low cloud formation. The shading shows the 95% confidence mean air temperature anomalies at 2 m averaged over the 30-year analysis period for the 2010 mid-latitude MCB case. Arrows not drawn to scale.
Extended Data Fig. 4. 2010 transient surface temperature and pressure response to subtropical MCB. 2010 subtropical MCB annual mean changes in reference height air temperature overlaid with changes in near-surface winds (~993 hPa; arrows) (a, c, e, g) and sea level pressure (b, d, f, h) for the first 4 years of the simulation.
Extended Data Fig. 5. Present and future responses in summer apparent temperature and annual mean precipitation under subtropical MCB. a, Change in bias corrected summer (JJA) apparent temperature [see supplementary materials, eq. 1] and (b) annual mean precipitation under 2010 subtropical MCB compared to no MCB. c, the same as (a) and (d) the same as (b) except for the responses under 2050 conditions. Ocean and insignificant (p>0.05) values are masked out.
Extended Data Fig. 6. Atlantic Meridional Overturning Circulation response to mid-latitude MCB and future warming. Change in Atlantic Meridional Overturning Circulation (AMOC) to mid-latitude MCB under 2010 conditions (a) and 2050 conditions (b). c, Change in AMOC due to warming under SSP2-4.5 without MCB. d, Change in AMOC between the 2050 mid-latitude MCB and 2010 no MCB cases, where near-zero values indicate a restoration of present-day conditions from MCB. The x-axis shows the latitude of the zonal mean, the y-axis shows depth from the sea surface, and the shading shows the AMOC strength in Sverdrups (Sv). 30-year difference from monthly mean output is plotted. Note the different color bar scale to Fig. 4a.
Extended Data Fig. 7. Atlantic Meridional Overturning Circulation response to subtropical MCB and future warming. Change in Atlantic Meridional Overturning Circulation (AMOC) to subtropical MCB under 2010 conditions (a) and 2050 conditions (b). c, Change in AMOC due to warming under SSP2-4.5 without MCB. d, Change in AMOC between the 2050 subtropical MCB and 2010 no MCB cases, where near-zero values indicate a restoration of present-day conditions from MCB. The x-axis shows the latitude of the zonal mean, the y-axis shows depth from the sea surface, and the shading shows the AMOC strength in Sverdrups (Sv). 30-year difference from monthly mean output is plotted. Note the different color bar scale to Fig. 4a.
Extended Data Fig. 8. Change in Atlantic Ocean northward heat transport from MCB. Heat transport response to mid-latitude MCB (orange) and subtropical MCB (blue) in 2010 (solid) and 2050 (dashed). Positive values indicate a zonally integrated northward transport of heat in Petawatts (PW). 30-year differences from monthly mean output are plotted.
Extended Data Fig. 9. Change in 2050 near-surface temperature and heat flux from MCB. 

a, c, Change in annual mean 2m air temperature overlaid with climatological mean winds. b, d, Change in surface heat flux to mid-latitude MCB (a, b) and subtropical MCB (c, d) under 2050 conditions. Insignificant (<95% CI) values are masked out and the top right value in each panel is the area-weighted global mean. The magenta and green polygons show the annual mean mid-latitude and subtropical cloud brightening regions respectively.
Extended Data Fig. 10. Future change in monthly low cloud fraction due to warming. Monthly mean changes in modeled low cloud fraction under 2050 warming from SSP2-4.5 emissions without MCB relative to the 2010 control. Insignificant (<95% CI) values are masked out.
Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- WNARegionalMCBNatureS1v1.pdf