Reply to the comments of the manuscript entitled "The effectiveness of solar radiation management for marine cloud brightening geoengineering by fine sea spray in worldwide different climatic regions" by Zhe Song et al.

We truly appreciate the reviewer for all the constructive comments and suggestions. We have adopted all of the suggestions in our revised manuscript. The followings are our point-to-point responses to the reviewer's comments. The responses are shown in **brown and bold fonts,** and the added/rewritten parts for the revision are presented in **blue and bold fonts**.

Reply to Reviewer #1:

This study explores Marine Cloud Brightening in five regions across the global ocean using the WRF-CMAQ model. Their results show that clouds are most susceptible to brightening in the North Pacific, South Pacific, and South Atlantic where marine stratocumulus dominate, this finding is consistent with previous studies. The authors look at MCB in the Western Pacific, a region they call Asia, and an equatorial region in the Philippine Sea they call Equa. In each region, the authors explored injecting Accumulation mode sea salt particles in four experiments which differed by the amount injected and whether the injection rate was sensitive to wind speed.

While the analysis is expansive, 11 main figures and 29 supplemental figures, their key points and a central storyline was very difficult to follow. I also see major issues in their methods which I will describe below. I think this paper will benefit from simplifying their paper goals, which I think is stated on line 345-347, "… when implementing geoengineering measures [MCB], it is essential to comprehensively consider the interactions between aerosols and clouds … in various regions". The authors may choose to add aerosol direct effects to this main message, but I think the paper would benefit in focusing on why MCB works in different ways in different regions. To reach this goal with more clarity and ease for the reader, the results could be presented as the SW_TOT, SW_CLD, and SW_AER findings for each region and why the results differ regionally. Is it cloud cover?, cloud type?, saturation issues?. I think having four different injection methods (+ analysis of injection in sensitive areas, which was not described in the methods) makes this storyline difficult to follow. In summary, reducing some of the analysis, and certainly the number and references to supplemental material, will clarify this paper and provide focus which will enhance readability. The main points of the paper and which results are unique to this study, are currently difficult to decipher amongst the details.

Response:

Thanks a lot for your detailed feedback on our paper. We adopted these suggestions to improve the structure of the paper. In this paper, we tested the effect of MCB under different injection strategies in five open ocean areas using a regional model, and discussed the regional differences in radiation in Section 3.2 of the original paper and the effect of cloud properties on SW_CLD in Section 3.5. We have improved our analyses by incorporating your comments below. In order to improve readability and clarity, we have streamlined the number of supplementary materials by reducing excessive references in the main text and moving some of them to the supplementary materials.

Thank you again for your detailed feedback on our work. These suggestions help us improve the quality of our manuscripts and make them easier for readers to understand.

Major Concerns:

1. There is only one simulation for each experiment and region. This makes the discussion of model uncertainty impossible and difficult to gauge whether the results would be consistent if other ensemble members were included. I recommend at least 3 ensemble members per region.

Response:

Thank you for pointing out the issue regarding model uncertainties. We have added perturbations by generating three ensemble members for each experiment in each region. The new results with error bars and dot plots of regions with significant variations in spatial distributions have been added in the revision. Thank you again for your suggestion that the addition of ensemble simulations allows us to more fully assess the reliability and uncertainty of the results (shown later).

2. There is no discussion of cloud cover, cloud height, and other cloud characteristics in the "Base" simulation. In fact, there is no description of Base in the Methods. What is the (Base) climatology of relative variables to MCB in each of the regions?

Response:

Thank you for pointing out the lack of descriptions in the "Base" case. We did describe the cloud fraction and cloud height for the sensitivity experiment simulations in L448-L455 in Section 3.4 of the original manuscript, but there was no specific discussion of cloud characterization for Base for each region. To add reviewer's concerns, we presented the cloud characteristics of each Base experiment in table and text form and described them in Methods in the revision.

Added/rewritten in Section 2.2:

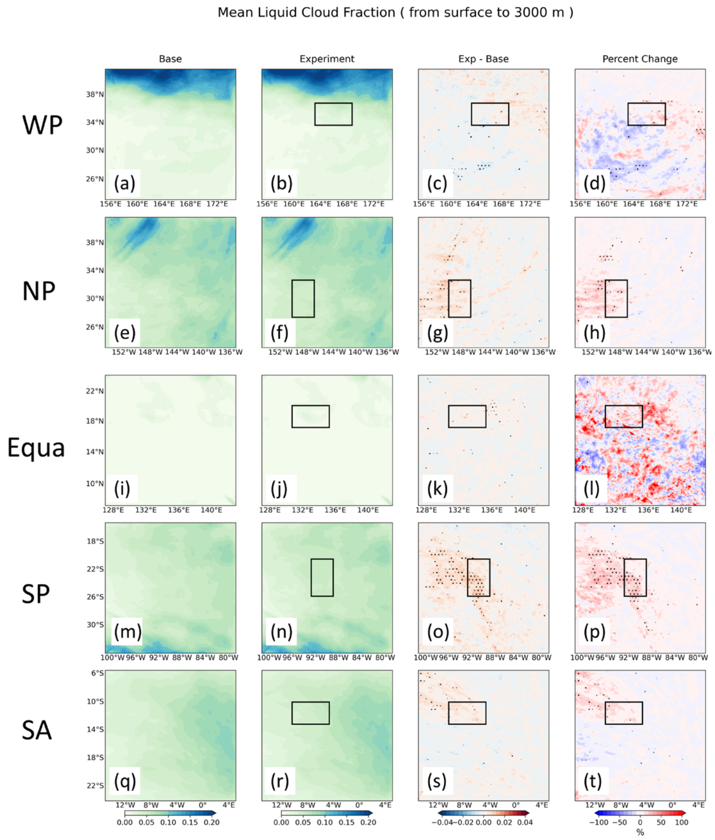
The results of the Base simulations with the model settings described above and default sea salt emissions (no aerosol injection) were obtained. As can been seen, there are significant differences in the cloud distributions for the five ocean regions in the Base simulations during the study period, with wider distributions of liquid clouds in the NP, SP, and SA regions, but fewer clouds in the WP and Equa regions (Fig. 2, first column). Cloud heights are distributed between 500–2000 m, centered at 1000 m (Fig. S1, first column). The cloud fraction, CDNC, liquid water path (LWP), and sea-salt aerosol concentrations in the Base simulations for each region are summarized in Table 1.

3. Moreover, there is no description of "sensitive" regions in the Methods, nor how they were selected or why this analysis is essential to their paper. I suspect the sensitive regions are where there is cloud cover in the first set of simulations. But during the set of simulations to explore the "sensitive" regions, are you sure the clouds were still co-located with in the black box?

Response:

Thanks a lot for your comments. Our descriptions of sensitive regions are in Section 3.1

of the original manuscript, and we describe them in the Methods section in the revised manuscript (shown later). In fact, as the reviewer thought, there are strong relationships between sensitive areas and cloud coverages. Because SW_CLD play a major role when aerosol injection is low, the total shortwave radiation (SW_TOT) is more affected by clouds. When we calculate the sensitive areas, we are calculating those areas with the largest SW_TOT. So there are strong relationships between the sensitive areas and the cloud coverages. Figure S13 illustrates the cloud fraction (first column) and the selection of sensitive areas (second column) for each region in Base. As can be seen from the figure, most of the sensitive areas are in places with more cloud cover. Because of the need to stay away from the boundaries, the sensitive areas in some regions are not selected for analyses where there are the most cloud coverages. During the simulations, the locations of the sensitive areas did not change because the simulated domains and the input meteorological conditions remained the same. All that changed are the different injection methods and the amount of injections.



We have improved the description of how sensitive areas are designed in the methods section as follows:

Added/rewritten in Section 2.2:

Uniform injections of sea-salt aerosols throughout the region ignored aerosol transports and dispersion at the boundary. Therefore, based on the results of a fixed 10^{-9} kg m^{-2} s^{-1} injection rate, we identified the geographical regions (30 × 50 grid points, approximately 360 km × 600 km, away from the domain boundary) in five ocean areas where the TOA radiative perturbations caused by uniform injection were the largest, and the most sensitive. Table S3 shows the locations of these sensitive regions. The injection amount in the sensitive region at a fixed 10^{-9} kg m^{-2} s^{-1} injection rate is found to be about 1/20 of those in the full domain.

We have added information about the location of sensitive areas in each region in conjunction with comments from other reviewers as follows (Table S3):

Table S3. Grid coordinates and latitude and longitude ranges of sensitive areas.

Region	Start_x, End_x (in grid)	Start_y, End_y (in grid)	Start_Lat, End_Lat	Start_Lon, End_Lon
WP	(70, 119)	(98, 127)	(28.18, 31.66)	(156.7, 162.6)
NP	(40, 69)	(40, 89)	(24.86, 30.34)	(-153.4, -150.5)
Equa	(40, 89)	(103, 132)	(18.15, 21.25)	(130.0, 135.2)
SP	(65, 94)	(75, 124)	(-26.18, -20.84)	(-92.56, -89.06)
SA	(40, 89)	(101, 130)	(-13.77, -10.76)	(-13.03, -7.530)

4. Why were wind-dependent injection scenarios considered? If this study wants to explore where injections are most efficient, I don't think having wind-dependence is necessary. I would consider removing this analysis or include a justification.

Response:

Thank you for your suggestions. This paper attempts to explore the best strategy for injecting sea-salt aerosols, and exploration of where it is most effective is a part of the paper as well. We have found that many modeling studies had used wind-speed dependent injections, such as Korhonen et al. (2010), Hill and Ming (2012), Jones and Haywood (2012), Partanen et al. (2012), Pringle et al. (2012), and others. In this study, we would like to show that the strategy of wind-dependent injection led to the injection of large amounts of sea-salt aerosols in certain high-wind-rate regions, which led to the saturation of cloud radiative effects. This may affect the performance of the MCB in regional and global models. In contrast, injection of sea-salt aerosols at a fixed rate can identify geographic regions that are most sensitive to increased sea-salt aerosols and produce the largest TOA radiative perturbations.

We emphasized this result in Section 3.3 of the revised version:

Added/rewritten in Section 3.3:

Therefore, wind-dependent injection strategies led to the injection of large amounts of sea-salt aerosols in certain areas with high wind speeds, leading to saturation of cloud radiation effects, which might affect the performances of MCB in the simulations of regional and global models.

5. Why were Accumulation mode particles used? Connolly et al 2014 and Wood 2021 demonstrate that the optimal distribution of sea salt aerosols for MCB is 30-100 nm, or 0.03-0.10 um – in the Aitken mode. I would like to see this analysis completed with Aitken mode particle to get a better sense of marine cloud brightening as opposed to marine sky brightening.

Response:

Thanks to your suggestion, we have taken note of the findings of Connolly et al. (2014) and Wood (2021), which indeed suggested that Aitken mode (30-100 nm) sea-salt aerosols may

be more suitable for MCB, as mentioned in the Discussion section of the original paper. However, from an engineering realization point of view, there are significant technical challenges in generating and releasing such Aitken mode particles, which not only need high equipment requirements, but also more energy consumption (Cooper et al., 2013). Therefore, we chose to go for the accumulation mode aerosols that are more easily achievable in terms of regional large-scale application deployment. In addition, this study focused on the actual effects of MCB under different injection strategies in different climate regions, but did not discuss the influence of particle sizes on MCB. We understand the reviewer's concerns regarding the effect of particle sizes on MCB effectiveness, which is an important issue that deserves further exploration. We plan to focus on the effect of Aitken mode sea-salt aerosols on clouds in future studies.

Cooper, G., Johnston, D., Foster, J., Galbraith, L., Neukermans, A., Ormond, R., Rush, J., and Wang, Q.: A Review of Some Experimental Spray Methods for Marine Cloud Brightening, International Journal of Geosciences, 4, 78–97, https://doi.org/10.4236/ijg.2013.41009, 2013.

6. Where possible, can you also refer/cite tables and figures in the main text? It is difficult to read pages where the only tables or figures reference are in the supplemental. Can you combine some information into the main figures? – I would also recommend moving some of the results of supplemental analysis to the supplemental text. This may aid with the focus of the paper.

Response:

We thank the reviewer for the suggestions on the structure of our paper. We have consolidated and streamlined some figures, merged information and reduced reliance on the supplementary material in the revised version, and moved some of the descriptions to the supplementary material in order to improve the readability of the paper and ensure a clearer focus in the revision.

Minor Concerns:

1. Double check the verb tense that is used, the authors may find it easier to refer to their study and simulation results in the present tense.

Response:

We thank the reviewer for the careful corrections. We carefully examined the verb tenses in the paper and used the present tense to describe the findings in the revision.

2. The abstract could better capture what results were unique to this study and include a better justification for why this study is essential to the field.

Response:

We thank the reviewer for the feedback on the abstract. In our revised abstract, we emphasize the unique results of this study, which provide quantifiable data on radiation and

cloud variability for multiple regional MCB implementations, and suggest that injection strategies can be optimized by adjusting injection volumes and selecting sensitive regions in the simulations of regional models.

Added/rewritten in Abstract:

This study provides quantifiable radiation and cloud variability data for multiple regional MCB implementations and suggests that injection strategies can be optimized by adjusting injection amounts and selecting sensitive areas in the simulations of regional models.

3. Line 26 – "conducted experiments" sounds like field experiments, consider "designed computer simulations"

Response:

Thanks to the reviewer's suggestion. We have changed it to "designed model simulations" in the revision.

Added/rewritten in Abstract:

Here, we designed model simulations with injected sea-salt aerosols in the same framework for five open oceans around the globe.

4. Line 32 – remove the word "still"

Added/rewritten in Abstract:

As the indirect effect of aerosols saturates with increasing injection rates, the direct effect increases linearly and exceeds the indirect effects, …

5. Line 34-36 – This is a well-known characteristic of MCB and MSB, does your study offer any new findings?

Response:

Thanks a lot for your suggestions. We modified the abstract to emphasize our unique results.

Added/rewritten in Abstract:

This study provides quantifiable radiation and cloud variability data for multiple regional MCB implementations and suggests that injection strategies can be optimized by adjusting injection amounts and selecting sensitive areas in the simulations of regional models.

6. Line 44 -47 – unclear

Response:

Thanks to the reviewer's suggestion. We would like to add relevant background information to demonstrate the urgency of global warming and to provide a logical transition to the geoengineering methods introduced later in the paper. We will optimize the presentation

of this paragraph based on your suggestions to make it clearer and more closely serve the theme of the paper.

Added/rewritten in Introduction:

One of the key outcomes of the recently concluded 28th Conference of the Parties (COP28) was the completion of the first Global Stocktake (GST), a mid-term assessment of the progress made by countries toward achieving the climate goals of the Paris Agreement. However, the report highlighted that current efforts to reduce emissions had fallen short of the intended targets (https://www.cop28.com/).

7. Line 47 – attention (not attentions)
8. Line 47 – I don't think "radical" is the right word

Response for both comments #7 and 8:

Thanks to the reviewer's suggestion. We have deleted this expression in the revision.

Added/rewritten in Introduction:

Against this backdrop, scientists are turning their attention to more innovative geoengineering methods by attempting to reduce or offset the impacts of climate change through artificial interventions in the climate.

9. Line 61 – more sunlight back "to space"

Response:

Thanks to the reviewer's suggestion. We have rewritten this in the revision.

Added/rewritten in Introduction:

… thereby enhancing the cloud albedo, forming brighter clouds, and reflecting more sunlight back to space (the first indirect effect or Twomey effect).

10. Line 65 – what is meant by "coarse part"?

Response:

Thanks for the reviewer's suggestion. This should be expressed here as "coarse sea spray aerosols".

Added/rewritten in Introduction:

However, the effect of the coarse sea spray aerosols has an opposite effect that offsets the loss of liquid water path.

11. Line 66 – clarify that these are aerosols that are not injected into clouds

Response:

Thanks to the reviewer's suggestion. We have corrected the expression to make it clearer

in the revision.

Added/rewritten in Introduction:

Note that those aerosols were not injected into the clouds directly.

12. Line 69 – New Paragraph after "sea-salt aerosols as MCB."

Response:

Thanks to the reviewer's suggestion. We adjusted the paragraph structure in the revision.

13. Line 70 – non-polluting – I think terrestrial deposition of sea salt is pollution
14. Line 71 – You may wish to compare a global geoengineering intervention like SAI to MCB here.

Response for both comments #13 and 14:

Thank the reviewer for pointing out this problem. We understand that the deposition of sea-salt aerosols can have an impact on the terrestrial environment. We have revised this statement to "lower environment risks" and added references to more accurately reflect its environmental impact. We have clarified the object of comparison.

Added/rewritten in Introduction:

Compared to other geoengineering schemes, such as stratospheric aerosol injection (SAI), MCB has unique advantages. For example, the sprayed aerosols have lower environmental risks and can be applied locally to change the regional climate (Latham et al., 2008).

15. Line 76 – "summarizes" – I would use the present tense to describe the results in this paper.

Response:

Thanks to the reviewer's suggestion, we adjusted the narrative tense of the article.

Added/rewritten in Introduction:

Table S1 summarizes the results of current modeling simulations on MCB with sea-salt aerosols, as well as their implementation strategies.

16. Line 83-86 – sentence is unclear

Response:

Thanks for the reviewer's suggestions. We have revised the presentation to ensure clarity of sentences and to clarify the regions where MCB was implemented and the focus of their researches. Thank you again for your suggestions.

Added/rewritten in Introduction:

The implementation region of MCB is crucial. Existing studies have focused on the impacts of MCB implementation in three key areas: open oceans, equatorial region (between

30°S and 30°N), and coastal areas with widespread marine stratocumulus clouds.

17. Line100 – "considers" not "considered" – please correct all of these grammatical errors for next submission.

Response:

Thanks to the reviewer's suggestion. We corrected all grammatical errors and tense expressions in the revision according to the reviewer's suggestions.

Added/rewritten in Section 2.1:

The two-way coupled WRF (v3.4) - CMAQ (v5.0.2) model that considers both direct and indirect effects of aerosols was used in this study.

18. Line 141 – Did you consider calling the "Asia" region the "West Pacific (WP)"

Response:

Thank you for the valuable suggestions on our manuscript. We have revised "Asia" to West Pacific (WP) to accommodate the more common terminology. All charts and text descriptions have been modified in the revision

19. Can you justify why you chose to look at the Asia and Equa regions? I'm not sure I understand why these were a focus of the study.

Response:

Thanks for the reviewer's suggestions. There have been some previous MCB studies focusing on these two regions, like Kim et al. (2020) who studied the impact of MCB on East Asia (20-60° N, 90-160 °E) (Kim, D.-H., Shin, H.-J., and Chung, I.-U.: Geoengineering: Impact of Marine Cloud Brightening Control on the Extreme Temperature Change over East Asia, Atmosphere, 11, 1345, https://doi.org/10.3390/atmos11121345, 2020). More studies have been done on sea-salt aerosol injection in equatorial regions. Therefore, we selected several regions to make more extensive comparisons and explored the implementation effects and influencing factors of MCB in different regions.

20. Line 163, not 1.5 times the wind speed, but raised to the 1.5 power.

Response:

Thanks to the reviewer's suggestion. We combined it with another reviewer's suggestion and changed it to "raised to the power of 1.5" in the revision.

Added/rewritten in Section 2.2:

The threshold wind speed was set to 7 m s^{-1} and the spray efficiency at lower wind speeds raised to the power of 1.5.

21. Line 185 – “excluding the (direct effect) of the aerosols”

Response:

Thanks to the reviewer's suggestion. We correct it in the revision.

Added/rewritten in Section 2.3:

The responses of SW_TOT to the injections of sea-salt aerosols could be divided into the cloud radiation effects (SW_CLD, excluding the direct effect of the aerosols) and direct scattering effects when clouds are present (SW_AER).

22. Line 196 – Indent new paragraph

Response:

Thanks to the reviewer. We indented new paragraphs in the revised manuscript as suggested.

23. Line 198 – reference table S2

Response:

Thanks to the reviewer. We added the reference in the revised manuscript as suggested.

Added/rewritten in Section 2.3:

Therefore, we propose the concept of MCB efficiency (E_{MCB}) to measure the relationships between the amount of sea-salt aerosol injections and the resulting radiation flux responses (Table S2).

24. Line 220 – “Base” is not defined. Please discuss the Base simulation and climatology of these regions in the Methods.

Response:

Thanks for the reviewer's suggestion. We incorporated your previous advice into the methods to add a description of how to obtain Base simulations and the climatology.

Added/rewritten in Section 2.2:

The results of the Base simulations with the model settings described above and default sea salt emissions (no aerosol injection) were obtained. As can been seen, there are significant differences in the cloud distributions for the five ocean regions in the Base simulations during the study period, with wider distributions of liquid clouds in the NP, SP, and SA regions, but fewer clouds in the WP and Equa regions (Fig. 2, first column). Cloud heights are distributed between 500–2000 m, centered at 1000 m (Fig. S1, first column). The cloud fraction, CDNC, liquid water path (LWP), and sea-salt aerosol concentrations in the Base simulations for each region are summarized in Table 1.

25. At the end of the Methods please include a paragraph that describes the analyses to follow – how will they be presented? Why simulation will be compared to one another? Are these results

for regional averages/temporal averages, etc.

Response:

Thanks to the reviewer's suggestion. We added a paragraph at the end of the method to show how we calculated and compared the results.

Added/rewritten in Section 2.3:

The perturbations by generating three ensemble members for each experiment in each region were added. The results of all sensitivity experiments were compared to those of Base simulations. Unless otherwise specified, all results in this study are shown as overall regional monthly averages of the ensemble.

26. Line 236 – by discrepancy do you mean "variations in methods"?

Response:

Yes, thanks to the reviewer's suggestion. We have changed the description to make it clearer in the revision.

Added/rewritten in Section 3.1:

In modeling studies, variations in methods used to increase sea-salt aerosols may lead to different conclusions, and these variations may be one of the reasons for differences in the assessments of MCB potentials in the previous studies.

27. Line 239 – relies -> rely
28. Line 241 – Can you reference Figure 2 as well as Table S2?

Response for both comments #27 and 28:

Thanks to the reviewer's suggestion. We have corrected the grammatical errors and added the references for the figures and tables in the revision.

Added/rewritten in Section 3.1:

The Natural×5 and Wind-adjusted strategies, which rely on wind speeds, inject sea-salt aerosols of 0.031–0.085 and 0.18–0.21 × 10^{-9} kg m^{-2} s^{-1} into the five regions, respectively, and result in SW_TOT variations of 0.07–2.1 and 1.4–8.4 W m^{-2}, respectively (Fig. 3a and Table 2).

29. Line 246 – exceeded -> exceeds

Response:

In conjunction with another reviewer's comment, we have removed this sentence from the revised manuscript.

30. Line 257-260 – sentences and results such of this would benefit with a reference to a figure/figure panel at the end of the sentence to aid the reader in deciphering what result is being examined.

Response:

Thanks to the reviewer's suggestion. We have added the corresponding references for the figures and tables at the end of the sentence in the revision.

Added/rewritten in Section 3.1:

The Fixed-wind-adjusted strategy results in SW_TOT changes of 5.0–20 W m^{-2} in the five regions (Fig. 3a), …

31. Line 260-261 – unclear

Response:

Thanks to the reviewer's suggestion, we have deleted this sentence in the revision.

32. Line 269 – higher (than what?)

Response:

Thanks to the reviewer's suggestion. We would like to express that the first two injection strategies are higher than the other two injection strategies that inject more volume.

Added/rewritten in Section 3.1:

In the NP, SP, and SA regions, the E_{MCB} values of the Natural×5 and Wind-adjusted strategies with relatively small injection amounts are higher than the other two strategies with large injection amounts.

33. Line 270 – Emcb decreased (where?)

Response:

Thanks to the reviewer's suggestion. Since this statement is mentioned in section 3.3, we have deleted it from the revised version.

34. Line 272 – reference figure 3

Response:

Thanks to the reviewer's suggestion. We have added reference for this figure.

Added/rewritten in Section 3.1:

At the same injection amount, injecting at a fixed rate shows higher E_{MCB} relative to injections depending on wind speed, as consistently shown in all five regions (Fig. 3b).

35. Line 273 – were -> are

Response:

Thanks to the reviewer's suggestion. We have corrected it in the revision.

Added/rewritten in Section 3.1:

The productions of sea-salt aerosols in nature are strongly correlated with wind speed, …

36. Line 288 – ignored -> ignore
37. Line 290 – grid (points)
38. Line 288 – 306 – please explain the sensitive regions and why this analysis is done in the Methods

Response for comments # 36, 37 and 38:

Thanks to the reviewer's suggestion. Since the content describing the sensitive areas was moved to the method part, we have modified the sentences and deleted the relevant expression here.

Added/rewritten in Section 2.2 (Method):

Uniform injections of sea-salt aerosols throughout the region ignored aerosol transports and dispersion at the boundary. Therefore, based on the results of a fixed 10^{-9} kg m^{-2} s^{-1} injection rate, we identified the geographical regions (30 × 50 grid points, approximately 360 km × 600 km, away from the domain boundary) in five ocean areas where the TOA radiative perturbations caused by uniform injection were the largest, and the most sensitive.

39. Line 302-306 needs references.

Response: Thanks to the reviewer's suggestion. We have added the reference (Latham et al, 2014) in the revision.

Added/rewritten in Section 3.1:

Considering that the original intents of MCB or MSB design are regional application (hurricane mitigation, coral reef protection and polar sea ice recovery) (Latham et al., 2014) …

40. Below line 306 – I stopped making editing requests. Please review and have others look at the paper for grammatical and clarity errors before resubmission.

Response:

Thanks to the careful review of the reviewers. We have checked again for grammatical errors and made corrections in the revised manuscript.

41. Line 378-379 – Can the authors describe the variations in cloud types, cloud amounts (cover/fraction), and atmospheric conditions that make the SW_CLD response different in each of the 5 regions. I think this should be a main focus of the text.

Response:

Thanks to the reviewer's suggestions. By combined with your other suggestions, we describe them in Section 3.5 and discussion how cloud features affect SW_CLD responses in different regions.

42. Line 420- 447 – This could be supplemental text and figures

Response:

Thanks to the reviewer's suggestions. We retained the results of AOD and transferred the descriptions of other aerosol properties and physical properties to Supplementary Text S2.

43. Line 448 – 455 – Please move this discussion to the beginning of the results or in the methods as you describe the 5 locations. I think it would be helpful to have low cloud cloud fraction as a main figure as this will highly correlate with SW_CLD and help explain the results and how they differ amongst regions. This section I would consider expanding and adding details such as how variable cloud cover and cloud type affect your results.

Response:

Thanks for the reviewer's suggestion. We have combined your previous comments and moved this part into the method. In addition, we describe them in section 3.5 and discuss how cloud features affect SW_CLD responses in different locales.

44. Section 3.5 – can these results be summarized in a main text table?

Response:

Thanks to the reviewer's suggestion. We have summarized the driver results for CRF'param and SW_CLD in Table 3.

Added/rewritten in Table 3:

Table 3. Relative effects of cloud fraction and albedo changes on CRF'$_{param}$ and Twomey, LWP, and cloud fraction effects to SW_CLD responses after uniform fixed injection of 10^{-9} kg m^{-2} s^{-1} sea-salt aerosols over five ocean regions.

Areas	CRF'$_{param}$			$\frac{\Delta\alpha}{\Delta \ln AOD}$		
	$\alpha'_c\bar{f}$	$\bar{\alpha}_c f'$	$\alpha'_c f'$	Twomey Effect	LWP Effect	Cloud Fraction Effect
WP	71.5%	20.7%	7.82%	48.4%	41.6%	10.1%
NP	72.7%	16.9%	10.4%	48.5%	41.7%	9.71%
Equa	60.2%	27.3%	12.4%	36.4%	58.5%	5.09%
SP	73.8%	15.9%	10.3%	51.8%	39.0%	9.19%
SA	77.3%	13.9%	8.81%	52.5%	39.7%	7.78%

45. Figure 4 Caption – call it the y-axis not the vertical coordinate.

Response:

Thanks to the reviewer's suggestion. We modified the title corresponding to Figure 4.

Added/rewritten in Figure 4:

Figure 4. Decomposition of the upward shortwave radiative fluxes at the TOA due to the different strategies of injecting sea-salt aerosols in the five regions. Note that the y-axis ranges are not consistent.

46. In general for Section 3.2, I don’t see how you can interpret the result of SW_CLD and SW_AER without discussion what the cloud cover is. If there are no clouds, of course SW_AER will dominate.

Response:

Thanks to the reviewers' comments, we focus in Section 3.2 on the overall results of SW_CLD and SW_AER for the five ocean regions under different injection strategies. As you pointed out, the presence of clouds is one of the important factors affecting these two results. However, the focus of Section 3.2 is to present data on these radiations to exemplify the results of MCB - i.e., how the cooling effect is achieved by reflecting more solar radiation. Therefore, in this section we do not discuss in detail the specific influences of cloud cover. Instead, we provide a more in-depth analysis of the drivers of SW_CLD in Section 3.5, specifically discussing the contribution of different characteristics of clouds (e.g., cloud amount, liquid water paths, and Twomey effect) to SW_CLD. We have added a related note in Section 3.2, indicating that the effect of cloud properties on SW_CLD will be shown in Section 3.5 to pave the way for the subsequent analysis.

Added/rewritten in Section 3.2:

The effect of cloud properties on SW_CLD will be shown in Section 3.5.

47. Throughout the manuscript, when making a comparison, please make sure to write out which two experiments are being compared to one another.

Response:

Thanks to the reviewer's suggestion. We have clarified the object of experimental comparison in the revision.

48. The use of significant digits seems arbitrary.

Response:

Thanks to the careful inspection of the reviewer. We have paid attention to the use of significant digits in the revision and used the same significant digits when describing the same variable.

49. The discussion contains a lot of material that I'm not sure is relevant to the current study. Try to focus on results that are unique to this study.

Response:

Thanks to the reviewer's suggestion. We have streamlined the discussion section to focus on the quantitative results of this study for radiation and clouds, as well as a discussion of optimized injection strategies.

Reply to the comments of the manuscript entitled "The effectiveness of solar radiation management for marine cloud brightening geoengineering by fine sea spray in worldwide different climatic regions" by Zhe Song et al.

We thank you for all the constructive comments and suggestions. We have adopted all of the suggestions in our revised manuscript. The followings are our point-to-point responses to the reviewer's comments. The responses are shown in **brown and bold fonts,** and the added/rewritten parts for the revision are presented in **blue and bold fonts**.

Reply to Reviewer #2:

Song and coauthors present an analysis of the effective radiative forcing (ERF) from sea salt aerosol injection (SSA) using the WRF regional circulation model. SSA are injected in five different regions using a range of emission rates and patterns. It is found that the indirect forcing is non-linear and saturates at high emission rates, after which the direct aerosol effect dominates the ERF. The efficacy of the cloud forcing is also found to be strongly regionally dependent. These are effects that have been shown in coarse resolution global circulation models (e.g., Alterskjaer and Kristjansson, 2013; Stjern et al., 2018; Rasch et al., 2024), but have not been tested for these regions using an RCM. However, the authors do not sufficiently articulate what new information is provided by their analysis. For example, the advantages of the higher RCM resolution versus GCMs should be discussed. i.e., which processes are expected to be better represented at these resolutions?

Response:

We truly appreciate all the constructive comments and suggestions of the reviewer. In the Discussion section, we have mentioned the results of Alterskjaer and Kristjansson (2013), Stjern et al. (2018), and Rasch et al. (2024), among others, who have studied MCB at the global scale through GCMs. While these studies reveal the nonlinear effect of indirect forcing at high emission rates, they have not yet delved into the specific manifestation of this effect at the regional scale. In contrast, we show for the first time the nonlinear responses of sea-salt aerosols to effective radiative forcing (ERF) and the relationships between direct and indirect effects in different regions through RCM. In addition, our results show that cloud forcing effects differ significantly at the regional level, further emphasizing the need to use high resolutions when studying different regions.

The high resolution of the RCM better captures the processes of sea-salt aerosol generation, emission and dispersion. And the emitted sea-salt aerosols are fully involved in all the simulated physical processes. This provides more detailed and closer to the real cloud component variations, such as CDNC, liquid water path, cloud effective radius, cloud albedo, etc. The detailed cloud property variations are shown in Section 3.4. In the GCM studies, on the other hand, the details of localized clouds and aerosols are often simplified, and these cloud property variations will not be accurately captured in GCM due to their coarse grid. Therefore, GCM focuses more on climate change, such as sea temperature and ecology. RCM, on the other hand, can better resolve the details of cloud changes and improve the simulations of cloud microphysical processes. This is also the focus of MCB, i.e., how injected aerosols affect

clouds and thus radiation. Through RCM, we are able to see more clearly the nonlinear effects of sea-salt aerosols on cloud and radiative forcing in the region, which provides a more targeted scientific basis for the development of regional climate regulation strategies in the future. We have added this information in the Discussion section.

Thank you again for your detailed feedback on our work. These suggestions will help us improve the quality of our manuscripts and make them easier for readers to understand. We will make a comprehensive revision based on your suggestions.

Major Concerns:

1. All multi-panel figures should be labelled (Fig. 5, 7, 8, 10, 11).

Response:

Thanks to the reviewers' suggestions. We have labeled all multi-panel plots in the revised manuscript.

2、It makes sense to test NP, SP, and SA as they have extensive low cloud coverage, but as you show in Fig S13 the Equa and Asia regions have few clouds over most of the domains. What is the justification for testing these regions? Is the idea to investigate MSB in these regions?

Response:

Thanks to the reviewers' valuable comments. We have changed "Asia" to "West Pacific (WP)" to accommodate the more common terminology by taking into account the comments of other reviewers. The reason we chose the WP and Equa regions for testing is primarily to provide a comprehensive assessment and better understanding of the role and impacts of aerosol injections under different climatic conditions around the globe.

There have been some previous MCB studies focusing on these two regions, like Kim et al. (2020) who studied the impacts of MCB on East Asia (20-60° N, 90-160 °E) (Kim, D.-H., Shin, H.-J., and Chung, I.-U.: Geoengineering: Impact of Marine Cloud Brightening Control on the Extreme Temperature Change over East Asia, Atmosphere, 11, 1345, https://doi.org/10.3390/atmos11121345, 2020). More studies have been done on aerosol injection in equatorial regions. Therefore, we selected several regions to make more extensive comparisons and explored the implementation effect and influencing factors of MCB in different regions.

In addition, our study aims to evaluate the responses of both MCB and MSB, simultaneously. Although there is extensive low cloud cover in NP, SP and SA, cloud formations and distributions are affected by the dynamics of the atmospheric environment and the injected sea-salt aerosol may not always enter the cloud completely. Therefore, MCB and MSB will co-exist and they are complementary.

3. When describing the simulations, a range of geometric mean diameters is given (0.11 to 0.15 micron) - it would be useful to know the GMD values for each emission case, since going from 0.15 to 0.11 diameter would increase the number flux by >2x for the same mass flux. I suggest computing the forcing efficiencies per number flux to check if this explains the discrepancy

between the uniform emission and fixed wind adjusted cases.

Response:

Thanks to the reviewer's suggestion. To address your comments, we calculated the sea-salt injection efficiency in number fluxes and added the results in the revision.

Added/rewritten in Section 3.1:

Since the number flux of aerosols increased with the decreases of the injected aerosol particle size for the same mass flux, we examined the MCB efficiency in units of aerosol number concentration (Fig. S3). The results show that the number efficiency of MCB is proportional to the injection rate of aerosol number (Fig. S3c). In the same quality injected, the aerosol number varies greatly (Fig. S3d).

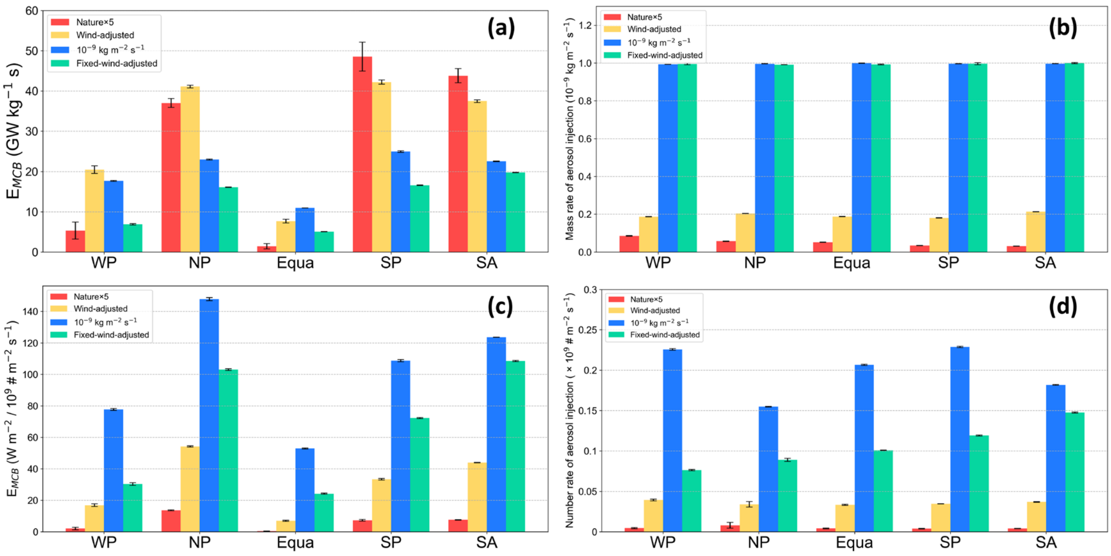


Figure S3. The MCB efficiency (a) and injection rates (b) in terms of aerosol mass, and MCB efficiency (c) and injection rates (d) in terms of aerosol number across different strategies in five ocean regions.

4. Recommend adding a figure displaying climatological sea salt aerosol concentrations and cloud fields (fraction, CDNC, LWP) for each region in the main body. The distribution of clouds within the simulation regions is a major explanatory factor in the strength of the SW cloud forcing, which should be incorporated into the interpretation of the forcing differences.

Response:

Thanks to your suggestion. By taking into account the comments of other reviewers, we have added a table (Table 1) in the Method of the main text to show the climatological sea-salt aerosol concentrations and cloud fields (fraction, CDNC, and LWP) for each region, and described the cloud distributions from Base's simulations in the Method. The effects of cloud fraction and other cloud properties on cloud radiative forcing are explained in Section 3.5.

Added/rewritten in Section 2.2 (Method):

The results of the Base simulations with the model settings described above and default

sea salt emissions (no aerosol injection) were obtained. As can been seen, there are significant differences in the cloud distributions for the five ocean regions in the Base simulations during the study period, with wider distributions of liquid clouds in the NP, SP, and SA regions, but fewer clouds in the WP and Equa regions (Fig. 2, first column). Cloud heights are distributed between 500–2000 m, centered at 1000 m (Fig. S1, first column). The cloud fraction, CDNC, liquid water path (LWP), and sea-salt aerosol concentrations in the Base simulations for each region are summarized in Table 1.

Table 1. The cloud fraction, CDNC, LWP, and regional sea-salt aerosol concentrations at

Areas	Cloud Fraction		CDNC (# cm^{-3})		LWP (g m^{-2})		Regional sea-salt aerosols (μg m^{-3})	
	Base	Exp	Base	Exp	Base	Exp	Base	Exp
WP	0.0445	0.0488	19.3	100.0	12.8	19.8	8.9	143.0
NP	0.0678	0.0760	9.7	60.2	24.6	43.9	7.2	126.0
Equa	0.00511	0.00594	17.5	83.4	0.8	1.4	7.3	102.0
SP	0.0547	0.0617	11.5	89.4	21.6	38.9	6.8	176.0
SA	0.0519	0.0575	12.3	92.2	23.5	41.6	7.00	149.0

Base and after injection of sea-salt aerosols at 10^{-9} kg m^{-2} s^{-1} (Exp) for five ocean regions.

5. Line 245-246/Line 299-300: I don't think it makes sense compare the global GHG radiative forcing to the regional average MCB forcing, since MCB can only be applied over part of the globe. You are also comparing MCB in its most effective season (summer) to annual mean GHG forcing. Both factors lead to overestimating the efficacy of MCB relative to GHG. It would be useful to also express the radiative forcing from the WRF simulations as a global annual mean forcing (i.e., ERF x [AREA_REG / AREA_GLOB] x [2 months / 12 months]) for a more apples-to-apples comparison of the forcing magnitude to the GHG effect.

Response:

Thank you for your careful review, and we agree that a direct comparison of the global greenhouse gas (GHG) radiative forcing to the regionally averaged marine cloud brightness (MCB) forcing is not appropriate. As you point out, the MCB only acts over a portion of the region, and the fact that we are comparing the MCB forcing effect during the most effective season (summer) to the year-round average GHG forcing could indeed lead to an overestimation of the MCB efficacy. So we removed the direct comparison between these two in the revised manuscript to avoid misleading conclusions. Thank you again for your review and constructive comments.

6. Fig. 9: Why does NP see a much lower activation rate of CCN to CDNC compared to SP/SA? It also appears to have a stronger cloud forcing 2x10^-9 kg/m2/s (Fig. 7) despite having a weaker increase in cloud albedo. What is the explanation for this difference, given that the cloud fraction effect is small?

Response:

Thanks to the reviewer. This is a good question. The much lower activation rate of CCN to CDNC in the NP region compared to SP and SA is mainly related to the method of calculation of CDNC. In this study, the CCN concentrations examined here were calculated on the basis of the results at the fixed 0.1% supersaturation. However, CDNC concentrations were calculated at the actual supersaturations which varied for different time and locations from the model simulations. This means that high CCN concentrations do not indicate the high CDNC because they depend on the meteorological fields when CDNC concentrations were calculated.

Regarding "It also appears to have a stronger cloud forcing 2×10^{-9} kg m^{-2} s^{-1} (Fig. 7) despite having a weaker increase in cloud albedo", this is because the cloud fraction in the NP is higher than other regions (Table 1, see above). Therefore, even if the change in cloud fraction due to aerosol injection has a small effect on cloud forcing, the NP region still has significant overall cloud forcing due to its high cloud fraction. When we express that the effect of cloud fraction is small in Section 3.5, we are referring here to the small effect on forcing due to the change in cloud fraction due to aerosol injection, but not to the cloud fraction in the region itself. It is precisely because the NP region itself has a high underlying cloud fraction that is able to produce a strong cloud forcing effect even with a small increase in albedo.

7. Section 3.5: You used two different decompositions to identify the albedo versus cloud fraction effect - the first gives a CF effect up to 23.8% but the second shows all CF effects are less than 10%. What is the cause of this discrepancy? Is there a reason you focus on the second decomposition rather than the first?

Response:

Thanks to the reviewer's question. This is caused by the difference in the purposes of the two decomposition methods.

Our first method calculates the cloud radiative forcing (CRF) parameter and quantifies the response of SW_CLD to changes in cloud cover and cloud albedo, as follows.

$$\mathrm{CRF}'_{param} = \alpha'_c\bar{f} + \bar{\alpha}_c f' + \alpha'_c f' \quad (7)$$

The second approach evaluates the impacts of injected aerosols on cloud radiative forcing through three effects (Twomey, LWP and cloud fraction effect).

$$\frac{\Delta\alpha}{\Delta \ln \mathrm{AOD}} = f\Delta\alpha_c(1-\alpha_c)\left(\frac{1}{3}\frac{\Delta \ln \mathrm{CDNC}}{\Delta \ln \mathrm{AOD}} + \frac{5}{6}\frac{\Delta \ln \mathrm{CLWP}}{\Delta \ln \mathrm{AOD}} + \frac{\Delta \ln f}{\Delta \ln \mathrm{AOD}}\right) \quad (8)$$

Briefly, the first calculation method focuses on changes in only the cloud itself, while the second calculation method, which includes AOD in the denominator, focuses on how cloud radiative forcing is affected due to aerosol injection by altering cloud properties (e.g., CDNC, LWP, and cloud cover). These two approaches are dealing with the complete two different things.

8. Add a supplementary table outlining the precise locations chosen for each "sensitive area" emission box. These simulations and the motivation for their inclusion should be described in the methods.

Response:

Thanks to the reviewers' suggestions. We have added a supplementary table (Table S3), which lists the specific location of each sensitive area in the revision to address the reviewer's concern.

Added/rewritten in Table S3:

Table S3. Grid coordinates and latitude and longitude ranges of sensitive areas.

Region	Start_x, End_x (in grid)	Start_y, End_y (in grid)	Start_Lat, End_Lat	Start_Lon, End_Lon
WP	(70, 119)	(98, 127)	(28.18, 31.66)	(156.7, 162.6)
NP	(40, 69)	(40, 89)	(24.86, 30.34)	(-153.4, -150.5)
Equa	(40, 89)	(103, 132)	(18.15, 21.25)	(130.0, 135.2)
SP	(65, 94)	(75, 124)	(-26.18, -20.84)	(-92.56, -89.06)
SA	(40, 89)	(101, 130)	(-13.77, -10.76)	(-13.03, -7.53)

Minor Concerns:

1. Line 53: "geoengineering" -> "SRM"

Response:

Thanks to the reviewers' suggestions. We have made this correction in the revision.

Added/rewritten in Introduction:

Among these, marine cloud brightening (MCB) has a certain realistic basis and is considered the most likely SRM method for regional applications

2. Line 66: "pass" -> "path"

Response:

Thanks to the reviewers' suggestions. We have made this correction in the revision.

Added/rewritten in Introduction:

However, the effect of the coarse sea spray aerosols has an opposite effect that offsets the loss of liquid water path.

3. Line 83: "post-treatment" -> "post-injection" ?

Response:

Thanks to the reviewers' suggestions. We have made this correction in the revision.

Added/rewritten in Introduction:

…, taking into account the post-injection processes of aerosols mentioned above.

4. Line 91: Expand WRF-CMAQ acronym when it is first used.

Response:

Thanks to the reviewer's correction. We have used the full name when first referring to WRF-CMAQ.

Added/rewritten in Introduction:

Here, we use the two-way coupled Weather Research and Forecasting - Community Multi-scale Air Quality model (WRF-CMAQ), …

5. Please provide some more details on the aerosol model. How many modes does the model use? What is the geometric standard deviation of the accumulation mode?

Response:

Thanks to the reviewer's suggestion. We have added the details of the aerosol model in the Method of the paper.

Added/rewritten in Section 2.1 (Method):

CMAQ represents the atmospheric particle distribution as the superposition of three log-normal modes, the Aitken, Accumulation, and Coarse modes (Binkowski and Roselle, 2003). The particle size distribution and the geometric standard deviation of the emitted sea-salt aerosols are adjusted to the local relative humidity before mixing with the ambient particle modes (Zhang et al., 2005). The geometric mean diameter of accumulation mode sea-salt aerosols in the CMAQ ranged from 0.2651 to 0.8187 µm, with the geometric standard deviation constrained between 1.76 and 1.83.

6. Line 163: "1.5 times the wind speed" -> "the wind speed to the power of 1.5"

Response:

Thanks to the reviewer's suggestion. We combined it with another reviewer's suggestion and revised it to "raised to the power of 1.5".

Added/rewritten in Section 2.2:

The threshold wind speed was set to 7 m s^{-1} and the spray efficiency at lower wind speeds raised to the power of 1.5.

7. Line 200: "It measured the efficiency" -> "this is a measure of the mass efficiency"
8. Line 200: "that was" -> "that is"

Response for both comments #7 and 8:

Thanks to your suggestion. We have modified the relevant tense expressions in the revision.

Added/rewritten in Section 2.3:

This is a measure of the mass efficiency of MCB implementing in different regions, that is, …

9. Line 246: "geoengineering" -> "greenhouse gas"

Response:

Thanks to your suggestion, we have removed the comparison between regional radiative forcing from the WRF model and global greenhouse gas radiative forcing in the revision based on your previous comments.

10. Line 312: "less injected" -> "lower mass injection"

Response:

Thanks to the reviewers' suggestions. We have made this correction in the revision.

Added/rewritten in Section 3.2:

The majority of the SW_TOT radiative flux response due to the lower mass injection Natural×5 and Wind-adjusted strategies is caused by the SW_CLD response

11. Line 326-330/Fig 4: How does this mechanism explain the lower "fixed-wind-adjusted" efficiency in Equa, where there is practically zero SW_CLD effect regardless of emission rate or strategy?

Response:

We thank the reviewer for the question. In the Equa region, the SW_CLD effect is very low regardless of the injection strategy or emission rate, mainly because the cloud fraction in this region is much lower than the other regions. As shown in the Table 1, the cloud fraction in the Equa region is only 0.0051, which is an order of magnitude lower than the other regions. The SW_CLD effect is close to zero because the region has almost no cloud coverage.

Areas	Cloud Fraction		CDNC (# cm^{-3})		LWP (g m^{-2})		Regional sea-salt aerosols (μg m^{-3})	
	Base	Exp	Base	Exp	Base	Exp	Base	Exp
WP	0.045	0.049	19.3	100.0	12.8	19.8	8.91	143
NP	0.068	0.076	9.67	60.2	24.6	43.9	7.18	126
Equa	0.0051	0.0059	17.5	83.4	0.85	1.4	7.32	102
SP	0.055	0.062	11.5	89.4	21.6	38.9	6.79	176
SA	0.052	0.058	12.3	92.2	23.5	41.6	7.00	149

Table 1. The cloud fraction, CDNC, LWP, and regional sea-salt aerosol concentrations at Base and after injection of sea-salt aerosols at 10^{-9} kg m^{-2} s^{-1} (Exp) for five ocean regions.

12. Line 361: "west and northwest of the injection areas" -> "west and northwest of the injection by the prevailing winds"

Response:

Thanks to the reviewer's suggestion. We have revised the expression to make it more rigorous.

Added/rewritten in Section 3.2:

The SW_CLD responses in NP, SP, and SA extend to the west and northwest of the injection by the prevailing winds, …

13. Line 363: "would be" -> "will be"

Response:

Thanks to the reviewers' suggestions. We have made this correction in the revision.

Added/rewritten in Section 3.2:

Changes in cloud microphysical properties will be presented later

14. Line 456-457: Recommend removing the first sentence here. The indirect effect is by definition the effect of aerosol on cloud microphysics and thus cloud radiative response, so this sentence is tautological.

Response:

Thank you for your advice. We agree with you and have removed the sentence to avoid unnecessary repetition.

15. Line 515: remove "on the other hand"

Response:

Thanks to the reviewers' suggestions. We have made this correction in the revision.

Added/rewritten in Section 4:

Other studies proposed that the direct scattering effects of aerosols may be more important.

16. Line 518: "depended" -> "depend"

Response:

Thanks to the reviewers' suggestions. We have made this correction in the revision.

Added/rewritten in Section 4:

Our results indicate that the importances of both aerosol direct and indirect effects

during MCB implementation depend on the injection strategies and the choice of injection regions.

17. Line 554-556: Note Wood, 2021 found that decreased activation due to competition may be overestimated in the Abdul-Razzak and Ghan activation parameterization used in many GCMs (e.g., by Alterskjaer et al., 2018; Rasch et al., 2024) relative to a parcel model.

Response:

Thanks to the reviewer's suggestion. We have noted this finding of Wood (2021) and have added it in the discussion section in the revision.

Added/rewritten in Section 4:

Notably, however, Wood (2021) found that decreased activation due to competition may be overestimated in the Abdul-Razzak and Ghan activation parameterization used in many GCMs relative to a parcel model.

18. Line 616: I don't see any basis for the statement that this study represents a lower limit on cooling, considering the large uncertainty in the cloud lifetime effect. Recommend removing this sentence.

Response:

Thanks to the reviewer's suggestion. We have deleted the relevant expression.

19. Line 622: "with the Geoengineering Model Intercomparison Project (GeoMIP) under the same framework" -> "with the same framework under the Geoengineering Model Intercomparison Project (GeoMIP)"

Response:

Thanks to the reviewers' suggestions. We have made this correction in the revision.

Added/rewritten in Section 4:

In Earth-system model studies, there has been a rich discussion of the climate and ecological impacts of the MCB with the same framework under the Geoengineering Model Intercomparison Project (GeoMIP).

20. Fig. 1: Which emission case is being plotted in the (a) panels?

Response:

Thanks to the reviewer for pointing this out. Fig. 1a plots the uniform injection of 10^{-9} kg m^{-2} s^{-1} sea-salt aerosols over the entire region. We have added this information in the caption.

Added/rewritten in Figure 1:

(a) The cumulative volume frequency of increased aerosol dry particle size (uniform injection of 10^{-9} kg m^{-2} s^{-1} sea-salt aerosols over the entire region).

21. Fig. 4 caption: "different ways" -> "different strategies"

Response:

Thanks to the reviewers' suggestions. We have made this correction in the revision.

Added/rewritten in Figure 4:

Figure 4. Decomposition of the upward shortwave radiative fluxes at the TOA due to the different strategies of injecting sea-salt aerosols in the five regions.

22. Fig 6 caption: "slash style" -> "hatching"

Response:

Thanks to the reviewers' suggestions. We have made this correction in the revision.

Added/rewritten in Figure 6:

Columns filled with hatching indicate the total radiative response outside the sensitive areas.