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Atmospheric Chemistry and Physics Discussions

Interactive comment on "A multi-model assessment of the efficacy of sea spray geoengineering" *by* K. J. Pringle et al.

Anonymous Referee #1

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Overall Comment: The research presented here utilizes three global climate models to understand the microphysical and thermodynamic conditions that influence the sign and strength of the cloud droplet concentration response in marine boundary layer clouds to artificial increases in sea spray aerosol. This paper builds on the wealth of existing literature and contributes novel results that are useful in understanding the efficacy of marine cloud brightening through a geoengineering approach. Results are summarized succinctly in the abstract and conclusion section. However, some clarification of the limitations of the method/approach and scientific arguments presented in this manuscript is needed, after which, this paper would be suited for publication in Atmospheric Chemistry and Physics.

Specific Comments: The scientific assumptions used in this paper mention on several

occasions that an increase in cloud droplet concentration (CDN) leads to increases in cloud albedo. This is only true if the macrophysical properties (principally liquid water path and cloud depth) of the clouds remain the same as CDN increases. The constant liquid water amount assumption was established by Twomey, (1974) as a simple way to predict how the cloud albedo would respond to increasing cloud condensation nuclei (CCN). However, if a cloud loses liquid water as CDN increases (e.g. through entrainment drying), the cloud brightening response diminishes and dimming can even occur. This kind of response has been observed in numerous ship track studies. Ship tracks serve as a useful analog to understanding the efficacy of geoengineering. Numerous in situ and satellite studies of ship tracks demonstrate that in general, the amount of liquid water (e.g., [Durkee et al., 2000],[Coakley and Walsh, 2002],[Segrin et al., 2007]), cloud depth (e.g., [Taylor and Ackerman, 1999], [Christensen and Stephens, 2011]), cloud cover [Rosenfeld et al., 2006], and cloud lifetime [Christensen et al., 2009] is significantly altered by the aerosol plumes from oceangoing vessels. In addition, significant evidence is lacking on whether the emissions from ships even influence the global albedo (Schreier et al., [2007], Peeters et al., [2011]). The authors mention the results of a large eddy simulation in Wang et al. (2011) on Pg. 7129, line 15, which highlight aspects of the macrophysical changes that these clouds undergo in response to increased CDN, the response of which partially depends on boundary layer precipitation and free-troposphere humidity. I believe much more needs to be said on this point, particularly in regards to the mounting body of evidence from ship tracks, because the current study is limited in its ability to represent the macrophysical changes of the clouds as CDN increases.

The spatial and temporal resolution should be specified for each model. Further information regarding the limitation of using these models using an offline approach should be provided? For example, one of the limitations is discussed on line 6 of page 7138 where it is stated that collision/coalescence is not treated. Does this also extend to cloud top entrainment as well? These processes are key to the maintenance of boundary layer clouds and how the albedo responds to elevated concentrations of cloud

droplets. I wonder if you would see the same response in Figure 8 if drizzle were included. A stronger updraft will promote higher supersaturations and hence, CDN, but rainfall acts to oppose that response through depleting CCN and CDN. There is seemingly no bound on the CDN increase through injection when the updraft speed is greater than 0.4 m/s and, at these updrafts speeds rainfall is likely to occur. This limitation casts some doubt on the accuracy of these results as they likely serve as an upper bound on the CDN concentration response to geoengineering. Due to these limitations, the responses reported in this study likely represent "instantaneous" microphysical changes of the clouds and miss important cloud feedbacks that can have negative adjustments to the CDN and cloud albedo responses on timescales of hours to days [Wood, 2007]. It is thus, recommended to discuss the breadth of the aerosol indirect effect responses and how effective this approach/model is at capturing them.

How is the updraft speed calculated? Is it an average over all cloudy grids at the cloud base height that is taken to be 940 hpa? Also, is it the same at every grid location in the model (i.e., the mean of w = 0 with a standard deviation of 0.25 m/s)? Is this an appropriate assumption given the average range of updraft speeds across the planet? Please clarify.

Technical corrections: 1) Punctuation and grammatical errors are speckled throughout the manuscript. Below is a list highlighting some of them.

2) The notation of units is non-standard. A space should be included between units. For instance, "m sˆ-1" should be used, not "msˆ-1"

3) Page 7126 line 1, we are talking about low-level clouds so I would add the word "boundary layer" after marine.

4) Pg. 7126 lines 4-6, this sentence in the abstract is a little vague. Can the author's clarify what the previous modeling study was (e.g., a reference), what a modest increase in CDN is (e.g., a % increase), and what a plausible emission scenario looks like (e.g., an injection rate)? I believe Salter et al., 2008 , lays this out nicely.

5) pg. 7126 line 12, "0.1 msˆ-1"? (Presumably the authors meant meters per second rather than inverse milliseconds.)

6) pg 7126 line 23, I'm not sure what a cloudy grid box means in this context, can it be changed to something like, "50% of the region covered by clouds"?

7) Pg. 7126, lines 22 – 25 need to clarify and explain how a stronger updraft allows for a higher CDN to be achieved. You might recast it to say something like this → "However, at stronger updraft speeds, higher values of CDN are achievable due to the elevated in-cloud supersaturation. Achieving a value of 375 cmˆ-3 in regions dominated by stratocumulus clouds with relatively weak updrafts cannot be attained regardless of the number of injected particles, thereby limiting the efficacy of sea spray geoengineering."

8) Pg. 7127, line 10, an increase in the planetary/cloud albedo would only arise if the macrophysical properties of clouds remained constant as CDN increased.

9) Pg. 7127, line 21, remove "of" and replace it with "that can range from"

10) Pg. 7127, line 24. The word online/offline is used numerous times throughout this manuscript. For the reader who is not familiar with a modeling study and their association to that word is through the world wide web, it might be useful to explain what is meant by a calculation being performed offline.

11) Pg. 7127, lines 25 – 28, Please clarify the impacts (climate I presume?) and emission rates (which ones? sea spray geoengineering? Or through natural wind-driven processes) that are being discussed.

12) Pg. 7128, line 1. Clarify what is competing for the moisture, is it the cloud drops (active), haze drops (inactive), or aerosols?

13) Pg. 7128, line 3. At the end of the sentence I might add, "to have a cooling influence on climate."

14) Pg. 7128, lines 4 – 7. Numerous commas are needed and the verb tense needs to

be consistent throughout this sentence. Also, what is a host model?

15) Pg. 7128, line 10. Please explain what is meant by the word “scenarios”? Does this refer to a geoengineering scenario, or something about the cloud parameterization scenarios that limited their ability to understand the response?

16) Pg. 7128, line 19. Missing a word between “CDN” and “be”.

17) Pg. 7129, line 1. Add “into cloud droplets” after the word “activate” and before “depends.” On point (ii), it is primarily the concentration of the background aerosol “serving as cloud condensation nuclei” that control the CDN concentration, not simply, the background aerosol.

18) Pg. 7129, line 10. This finding is inconsistent with that of Hobbs et al., [2000] where the concentration of CDN was found to principally depend on the size of the emitted particles. When oceangoing vessels burned diesel fuel or low-grade marine oil, the bulk of the produced particles in the exhaust were in the accumulation mode (0.03 – 0.05 um) and, ship tracks were generally produced using this fuel type. Particles produced from gas and steam-turbine engines were commonly too small to serve as CCN and thus, did not increase CDN or produce ship tracks.

19) Pg. 7130, line 7. The authors state that this assessment provides an upper bound on the CDN increase and potential radiative cooling. This is probably a correct assumption because “the model/approach does not account for negative adjustments to the CDN through cloud macrophysical changes (changes in liquid water amount, cloud depth, drizzle, ect..).” Therefore, I would simply state “(for macrophysically identical clouds)” after the words “in CDN” and before the word “which.”

19) Pg. 7131, line 25. Please explain what the optimum conditions are. I assume the authors mean, the optimum conditions for enhancing CDN concentrations?

20) Pg. 7132, line 6. Do the authors mean, an annual mean increase “in CDN concentration?”

21) Pg. 7133, line 3. This sentence might sound better if reworded: “. . . we found that at the updraught speeds considered, the number. . .”

22) Pg. 7133, line 10. Replace the word “on” with “of.”

23) Pg. 7134, line 4. Is VOCALS an acronym? If so, spell it out the first time it is used, which I believe is here. Also, there are an assortment of other acronyms (mostly model names) that should be spelled out throughout the manuscript as well.

24) Pg. 7134, line 17. Change “an” to “a” and, add units to the standard deviation, I’m assuming its in micro meters. On that note, the units are missing in a variety of locations throughout the manuscript. Also, can the authors provide an average value for the fraction of the aerosol size distribution that is larger/smaller than the injected mode?

25) Pg. 7134, line 17. The change in cloud albedo is “proportional” to the percentage change in CDN under constant changes in liquid water content.

26) Pg. 7135, line 24. Can the word “conditions” be explained in the following phrase “but the exact value depends on the conditions?” Do the conditions refer to the updraft speed or to the background aerosol concentration? Please clarify.

27) Pg. 7138, line 25. Higher concentrations of CDN were probably observed in closer proximity to the coast due to the industrial complex of copper smelters along the Chilean coast whose combined sulfur emissions total 1.5 TgS yr-1. This is comparable to the entire sulfur emissions from large industrialized nations such as Mexico and Germany.

28) In Figure 6, every region exhibits the same behavior, thus I think the paper could be cleaned up a bit by only including one of them. Is it possible to also include the average CDN concentration under the no injection (d000) scenario for comparison?

29) Pg. 7141, line 10, It is stated that increasing the injection diameter above 160 nm reduces CDN. The figure indicates otherwise. I would replace the word “reduce” with

“has a smaller influence on enhancing the concentration of CDN”.

30) Again, I would reduce Figure 7 to include the results from one region. Better yet, figs 6 and 7 could be combined using the results from only one region and the similar results from the remaining regions could be discussed in the text? Removing these figures would increase readability and enable easier navigation of the paper. This is a recommendation and, the decision to remove the content is entirely up to the author’s.

31) Pg. 7142, line 7. I’m not sure which system is being referred to at the start of this line, presumably the authors meant the “climate” system?

32) Pg7144 – 7145. The authors discuss the role of the dilution of ship plumes in stratocumulus. Hudson et al., (2000) and Ferek et al., (1998) provide evidence of this effect – i.e., whereby higher concentrations of CDN (and lower supersaturations) are generally observed closer to the ships and tend to decrease down the lengths of ship tracks. To my knowledge, there is currently no evidence for a reduction in the CDN concentration by the aerosol plumes from ships.

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