Response to Referee 2 Comments on "The G4Foam Experiment: Global Impacts of Regional Ocean Albedo Modification," by C. J. Gabriel et al.

Referee comments are in black. Responses are in blue.

1) The introduction session is a bit too long. Some of the background information for geoengineering in general, motivation and review can be shortened.

We agree and have removed the excess background information on geoengineering, reduced the length of the motivation section and the amount of literature review. Please see the new, ~35% shorter, introduction section. We were also able to remove some redundant language in sections 2-4 to make the paper a bit shorter.

2) In many of the figures results are shown and discussed in terms of both annual mean and June-July-August (JJA) seasonal mean. It is unclear why JJA, which is neither austral summer nor the exact monsoon season in the northern hemisphere, is discussed in particular, as opposed to other seasons.

JJA is chosen because it is meteorological summer in the NH and using JJA facilitates comparison with G4SSA, which reports results in terms of JJA (Xia et al., 2016). However, the Indian Monsoon season is typically defined JJAS, and we would use JJAS as our summer/wet monsoon season if we were focusing primarily on the Indian monsoon, or even exclusively on the Asian monsoon more broadly. Not all precipitation that is of interest in this study is monsoon precipitation, and various monsoon regions do experience somewhat different wet monsoon seasons. The cloud and temperature responses that are most of interest to highly cultivated and populated regions are best expressed by using JJA, since the NH is at its warmest during that meteorological season. Future work associated with the G4SSA and G4Foam simulation may look at, among other things, possible changes in monsoon onset and withdrawal in various geoengineering scenarios relative to what will happen under the RCP scenarios.

We add a summary of this reasoning to the text at lines 286-288 of the revised manuscript.

3) The color scheme in Figures 6-8 is different from that in Figures 3-5. This is fine, but using warm colors for decreases (i.e., negative changes) and cold colors for increases is a little inconvenient. Is there a particular reason for this?

Yes. The green is intended to signify a wet anomaly, and the brown is used to signify a dry anomaly. This color scheme is only used for hydrological variables precipitation, evaporation and precipitation minus evaporation (P-E). The colors we used are the traditional ones used for those variables, for example in the IPCC reports and in NOAA's Palmer Drought Index maps.

4) Line 76 (also in the caption of Figure 1): the phrases of "daily average" and "fixed daytime value" are inconsistent and a little confusing. My understanding is that the albedo is changed from one constant value to another. Is that right?

The albedo is actually changed from a value with a very small daily cycle that has a daily average value of 0.06 to a constant value of 0.15 (with no daily cycle) in the "foamed" regions. The inconsistent language has been removed. Please see that section, now at lines 50-55 and line 57-65, as well as the caption to Figure 1, which more clearly explains the change in albedo we imposed in the model. We have also added the caveat that an actual foamed region would likely exhibit fluctuations in albedo for many reasons and that additional study of the foam itself would be necessary to provide sufficient information to include fluctuations in foamed region albedo in future modeling studies. This could result in a slightly different surface energy budget than the constant albedo foam modeled here.

"RCP6.0 and G4SSA are run with an ocean surface albedo that contains a very small daily cycle, but the average albedo over a day is 0.06. The albedo of the ocean surface is raised from this daily mean of 0.06 to a constant value of 0.15, with no daily cycle, over the subtropical ocean gyres in the Southern Hemisphere, specifically 20°N-20°S, 90°W-170°W (South Pacific), 20°N-20°S, 30°W-0°E (South Atlantic) and 20°N-20°S, 55°E-105°E (South Indian) (Fig. 1). Everywhere else, ocean surface albedo in G4Foam is calculated the same as in RCP6.0 and G4SSA."

5) Lines 88-99: please clarify the use of acronym SSI (versus SAI).

This was an error in editing. We now define stratospheric sulfate injections as SSI in the revised manuscript and SSI is used exclusively throughout to refer to stratospheric SRM. There is no mention of "SAI" any longer.

6) Lines 134: "the cloud feedbacks" are unclear.

We have changed "the cloud feedbacks" to "any cloud feedbacks." We are acknowledging that the effectiveness of the G4Foam forcing will be affected by how clouds respond to the forcing, that the nature of this response is unknown until we conduct the experiment, and that we consider clouds to potentially be a large source of uncertainty. Please see lines 122-125.

7) Lines 248-249: Is this likelihood larger in this area than other areas in the SH? Please explain.

You are correct to point this out. The likelihood is not necessarily larger and the reference to that likelihood has been removed. We were principally motivated to brighten those specific regions because of their low cloud fraction, low wind speeds, weak currents, and lack of biological productivity.

8) Lines 267-268: Is there a reference for the attribution of model improvements to finite-volume dynamical core?

Yes. The reference to Neale et al. (2013) has been added at line 228.

9) Lines 310-311: is there a problem in the phrase inside the double quotes?

No. We have removed the quotes.

10) Line 339: needs some hyphens for "clear sky top of atmosphere"

Hyphens added.

11) Lines 341-346: it makes more sense to show net all-sky TOA flux in Fig. 2, maybe along with the net cloud forcing. The clear-sky forcing is not what is really exerted to the climate system.

We agree and have added the new Figure 2, which shows net all-sky TOA flux (Figure 2a) and net cloud forcing (Figure 2b).The beginning of section 3.1, now at lines 290-305, now refers to the new Figure 2. Additionally, we now report changes in radiative forcing as the all-sky values, rather than the clear-sky values, since all-sky is what is actually exerted on the climate. Figure 3, showing clear-sky forcing, which is very similar to, and at the beginning of the simulation, is almost exactly equal to, the imposed ocean surface albedo forcing. Clear-sky SW TOA is now only shown to illustrate that the G4Foam forcing is more efficient in achieving cooling than G4SSA forcing.

12) Lines 366-373: need more evidence to support the explanation for the increase in low-cloud fraction over the three areas, where the relative humidity might have been already quite high. Why doesn't the increase occur in the entire downwind area?

We have revised the manuscript to provide a detailed explanation for the increase in low cloud fraction in the areas to the north and northeast of the three "foamed" regions. The new section is copied below and can be found at lines 329-373:

"The low cloud fraction increase in the three areas to the north and northeast of the G4Foam-forced subtropical surface regions is likely due to a stronger than normal trade wind inversion (TWI). The inversion develops when warm air is trapped above the atmospheric mixed layer due to large-scale subsidence and surface mixing of cooler air above these relatively low SST regions. The increase in low cloud fraction does not occur over the entire downwind area because SSTs increase from east to west, causing a change in the lower troposphere as you travel from east to west. Moving west, the stratocumulus layer, which is trapped under the inversion base, decouples from the mixed layer in the lower troposphere. The surface warming triggers more turbulence within the planetary boundary layer, which allows for enhanced cumulus mixing in the cloud layer, which entrains dry air, and the marine stratocumulus layer evaporates as you travel west.

"The subtropical high-pressure systems are stronger in G4Foam, due to the stronger than normal Hadley Cell, which enhances subsidence throughout the subtropics. Typically, a subsidence inversion is strongest over the center of the subtropical anticyclones, over cold currents (particularly the Peru Current), and over cooler than normal waters, which are subjected to enhanced upwelling in large part by trade winds on the periphery of the subtropical highs (DeSzoeke et al., 2016). The TWI becomes weaker and its base increases in height with distance towards the west and towards the equator as SSTs increase. This pattern is particularly evident in the Pacific, due to the larger geographical extent of the forced area.

"Specifically, under G4Foam conditions, the increased low cloud fraction areas are the result of the combination of enhanced large-scale subsidence (stronger Hadley cell) and a cooler than normal ocean surface. The cooler than normal surface waters are due to general cooling throughout the SH, as well as an increase in wind-driven upwelling over these areas of increased low cloud fraction, which are already prone to upwelling, large fraction of low clouds and high relative humidity.

"In these areas north of the foamed areas, the subsidence inversion is not quite as strong as it is right under the subtropical high. However, SSTs are artificially low, due to general cooling of the hemisphere and enhanced upwelling, driven by anomalously strong winds, and mixing of this anomalously cool surface air within the planetary boundary layer keeps the lowest levels of the atmosphere cool, keeping the marine air inversion base above the lifting condensation level, allowing stratocumulus clouds to form at low altitude, below the base of the inversion. Additionally, since SST is lower than air temperature in the areas of enhanced low clouds, the surface inversion is further maintained as a result of sensible heat flux from the atmosphere to the ocean. Ultimately, the strong inversion often results in more marine layer cloud formation and longer times for the clouds to dissipate. This response is consistent through the 2030-2069 period. This enhanced low-cloud fraction response is similar to the seasonal cycle of marine low clouds around the periphery of the subtropical highs (Wood and Bretherton, 2004; Chiang and Bitz, 2005; Wood and Bretherton, 2006; George and Wood, 2010; Mechoso et al., 2014).

"The relationship between the strength of the subtropical high, inversion strength and marine cloud prevalence can be elucidated by analogy to the behavior of the very well-observed marine low clouds off of the California coast. The strength of the inversion, and the prevalence of marine low clouds are modulated by the annual cycle with annual maximum low cloud extent in the summer, when the subtropical high is at its strongest.

"The increased low cloud fraction response is not seen above the actual G4Foam forced regions despite the cooler SST. The subsidence is so strong in these areas that the base of the inversion falls below the lifting condensation level, and few clouds form."

13) Lines 418-421: Please elaborate on "the temperature dependence of precipitation".

We have clarified this portion of section 3.2. It is rather evident that with global warming, specific humidity in the tropical planetary boundary layer will increase by 7% K^{-1}, scaling with Clausius-Clapeyron (e.g., Held and Soden, 2006). However, the processes involving precipitation are quite complex and while it is clear that global mean precipitation will increase as global mean temperature increases, there is a wide range of estimates in the literature of how much precipitation will increase per degree of global warming. In the revised manuscript, we refer to a review that collects estimates from the literature of how much precipitation will increase per degree of global warming. They estimate a 1.5%-3% K^{-1} range.

We then report the precipitation change in G4Foam, relative to both G4SSA and RCP6.0 and note that while global mean precipitation over land and ocean changes by about 2%-3% per degree of global mean temperature, the changes over land, especially over the tropics, are dramatically different. Precipitation actually increases over land in G4Foam relative to RCP6.0, despite 0.6 K of cooling and there is far more precipitation over land in G4Foam than G4SSA despite G4Foam being only slightly warmer. We've clarified the discussion in the revised manuscript.

We have also shortened the abstract by one sentence. Line 646-647 added to acknowledgements to thank you for your valuable comments.

References

Held, I. M. and Soden, B. J.: Robust responses of the hydrological cycle to global warming, J. Climate, 19, 5686–5699, 2006.

Neale, R., Richter, J., Park, S., Lauritzen, P., Vavrus, S., Rasch, P. and Zhang, M.: The mean climate of the Community Atmosphere Model (CAM4) in forced SST and fully coupled experiments, J. Climate, 26**,** 5150–5168, 2013.

Xia, L., Robock, A., Tilmes, S., and Neely III, R. R.: Stratospheric sulfate geoengineering could enhance the terrestrial photosynthesis rate, Atmos. Chem. Phys., 16, 1479-1489, doi:10.5194/acp-16-1479-2016, 2016.