Reviewer 1 comments

1 Summary

"But while the manuscript does show that changing the capacitance has an impact on the simulated SW radiation bias in the SH, the impact on longwave (LW) radiation and the Northern Hemisphere (NH) are not sufficiently considered (the latter is only shown in the supplementary material and not discussed), although the agreement with observations decreases. Furthermore, the properties of ice containing clouds will depend on further uncertain processes in a GCM like aggregation (efficiency). Even without cloud ice forming in mixed-phase temperature regime the SW radiation bias in the SH is not fully removed (exp2). It remains therefore unclear whether the claimed improved simulation of clouds over the Southern Ocean still holds when other aspects are considered. Therefore publication in ACP cannot be recommended unless these issues are addressed."

We have modified the manuscript as per the points below.

2 Specific Points

1. P1L4: Is it more realistic to use the capacitance of Field et al. (2008) everywhere? In mixed-phase clouds (which occur frequently in the Southern ocean) riming can be important, hence more spherical ice particles can be present in these clouds.

Riming would eventually produce quasi-spherical particles, but in highly supercooled environments at water saturation, the growth due to deposition is likely to be faster. This is not only due to the high ice supersaturation but also because riming with cloud droplets is diminished. Observation by Harimaya (1975) shows that droplets with diameters less than 10 μm are too small to be collected onto ice crystals. Westbrook and Illingworth (2013) show some examples of pristine particles in supercooled layer clouds. Particles like these stellars have a capacitance close to the one we are using. Also the description of their fig5 points out the strong Z_{DR} (differential reflectivity) signal indicating non-spherical oblate particles.

References:

Westbrook, C. and Illingworth, A.: The formation of ice in a longlived supercooled layer cloud, Q. J. Roy. Meteor. Soc, 139, 2209–2221, doi:10.1002/qj.2096, 2013.

Harimaya, T., 1975: The riming properties of snow crystals. J. Meteor. Soc. Japan, 53, 384–392.

2. P1L9: The reduction of the bias of $\sim$4 Wm^{-2} should be put into context of the strength of the bias in the model. Also this reduction in SW bias is accompanied by an increase in the LW bias.

The reduction of SW cloud radiative effect of 4 W/m2 that we have shown is for the TOA since changes are more certain compared to the surface flux. As mentioned in the revised 'Observational data' section, the surface changes are prone to more uncertainties. CERES surface data itself depends on the uncertainties in the radiative transfer model.
Page 4; Section 2.2

3. P1L10-11: This is what Vergara-Temprado et al. (2018) have shown. What is your original contribution? In the conclusions it is written that INP's are not represented in the model, this can be mentioned in the abstract as well.

Removed the last sentence of abstract in the new version that mentions INP

4. P1L19: You mean in the Southern Ocean. These studies include for example Williams et al. (2013) and Lohmann and Neubauer (2018).

References added.
Page 1; Section 1

5. P2L20: For which years is the sea-surface temperature climatology computed? Is Schuddeboom et al. (2019) the right citation for AMIP simulations?

Reynolds SST for the years 1981 – 2012 has been used. Gates et al 1999 is the reference for AMIP (reference already included). Schuddeboom et al., 2019 is another study where a version of the control run used in of our study was used, hence cited it. Removed it to avoid any confusion.
Page 2; Section 2.1

6. P2L21: fig. 1 and further references to figures in the text: follow the manuscript preparation guidelines for authors of ACP

Corrected in the new version

7. P2L32: Why is the ventilation factor not considered in eq. (1)?

The capacitance value of 0.5 that we have used in our model does take into account ventilation factor as well (as per Field et al 2008) although it is challenging to quantify the effects of ventilation factor and deposition rates separately.

8. P3L7: For a sphere the capacitance is 0.5 x (maximum particle dimension). This is mostly difference in the naming convention or defining the 'capacitance'. Wesbrook et al., 2008 or Field et al., 2008 defines C = 0.5 for spheres and the product C*D is the capacitance. It is however conveying the same message. Essentially the default value of 'capacitance' is reduced from 1xd to 0.5xd in our study.

9. P3L9: Morrison and Grabowski (2008) use the capacitance of a sphere for small spherical ice and 0.48 times the capacitance for a sphere for unrimed nonspherical crystals, and a linear interpolation in between for partially rimed crystals. Morrison and Milbrandt (2015) use the same in the predicted particle properties (P3) scheme. This is an even more realistic representation of ice crystal capacitance. Could this be implemented in the Unified Model?

No, this approach cannot be applied in the Unified Model as we don't have a prognostic for riming fraction on ice like in their study.

10. P3L10-17: How is heterogeneous nucleation of ice represented in the model? Does it depend in ice nucleating particles (INP) concentrations or is it just a function of temperature (and if the latter, which function)? Not enough information is provided how heterogeneous and homogeneous freezing is implemented in the GA7.1*. What is the difference between the start-ice temperature and the all-ice temperature?

The control model does not have any ice-nuclei dependency for the heterogeneous nucleation. The heterogeneous nucleation temperature is simply following the temperature dependent function suggested by Fletcher [1962] (N. H. Fletcher. The physics of rainclouds. Cambridge University Press, London, UK, 1962). This then gets multiplied by a small 'seed' ice content for ice free clouds in order that the other micro physical terms can grow it. As far as homogeneous nucleation of liquid water is concerned, all liquid water at temperatures less than $-40°C$ is instantaneously frozen to form ice particles according to Rogers and Yau [1989]. (R. R. Rogers and M. K. Yau. A short course in cloud physics. Pergamon Press, Oxford, 3rd edition, 1989). At 'start-ice temperature', the detraining of liquid condensate as ice begins in the model and by 'all-ice tem-

perature', all condensate is detrained as ice. These details have been added in the revised version under Model set-up.
Page 3; line 12 - 29

11. P3L20-21: Since this is not a model version that has been already described in another publication, it needs to be mentioned whether the experiment setup is similar to another study, otherwise details need to be given here. Why is 12 hourly output used? This means that the diurnal cycle is not well represented in the simulations. CERES-EBAF provides a diurnally complete representation of Earth's radiation budget (Loeb et al., 2018).

Appendix modified (Page 8). In the newer version of the manuscript, we now use the daily-mean values for radiative fluxes from model

12. P3L22: ERA5 is a re-analysis dataset not an observational dataset.

We have removed ERA5 data in the new version. a modified Observational data section is included.
Page 4; Section 2.2 lines 7 - 12

13. P3L28-29: What was the reason to choose ERA5 as a reference for IWP given the large differences of IWP between different datasets (Duncan and Eriksson, 2018)? An uncertainty range for IWP should be added.

In the newer version, we are not using this comparison for IWP.

14. P3L31-32: Why are IWP/LWP shown only for these clouds? Shallow cumulus clouds may be interesting as well (Forbes et al., 2016).

The focus of this study is mostly on the stratocumulus boundary layer type clouds. Hence, we chose the corresponding types as mentioned in the main material of the manuscript. We have added analyses for other boundary layer types in the Supplementary material. A brief description of other types has now been included in the main material as well.
Page 4 ; lines 17-23

15. P4L1-2: Why is the analysis split into this boundary layer types? Either provide a motivation and discussion for the different boundary layer types or remove this split.

Similar to previous comment. More details included now.

16. P4L8 and all following occurrences: "w. r. t.": follow the manuscript

preparation guidelines for authors of ACP.

Corrected

17. P4L8-9: Why? Why does changing nucleation temperature not also impact LWP?

The zonal mean liquid water paths that we have shown here are dominated by the fronts mostly. So, even if ice nucleation temperature shows some sensitivity, they are mostly away from the frontal systems and mostly restricted to the shallow boundary layer types.
Page 4 ; line 30

18. P5L6: What does ". . . at surface well" mean? Rephrase.

Corrected

19. P5L13-14: That's an uncommon definition of SW CRE for model simulations. Typically two calls to the radiation routine are done, one with clouds and one without clouds. From these SW CRE is computed, taking into account cloud cover. How is SW CRE computed in partly cloudy gridboxes?

We have rephrased the sentence. In the model, for each grid box there is a cloudy and non-cloudy flux. From these fluxes, the CRE can be calculated using the amount of cloud fraction.
Page 5 line 32

20. P5L16-18: Why do exp1 and exp3 show a stronger reduction in SW CRE than exp2. In exp2 the least cloud ice should be present in the mixed-phase clouds so why is the SW CRE larger in exp2?

We do acknowledge some uncertainties in the effect of nucleation temperature on fluxes. There are some detrimental effects due to changes in the nucleation temperature that could be mostly due to the changes in the vertical distribution of the clouds affecting not just the low clouds but also the high clouds. By changing the nucleation temperature, we are essentially modifying the level at which freezing occurs. So, when we don't freeze the water lower down then it can go higher up in the atmosphere probably creating cirrus clouds and thus change the high cloud characteristics (thus affecting both short/long waves). A detailed examination of the effects on fluxes is not intended to be within the scope of this study. However, we do acknowledge the importance of this aspect and have incorporated that to be continued in future work. We have stressed this point and made more clarity in the discussion and conclusion sections.
Page 6 ; lines 20-25 and Page 7 ; lines 23-25

21. P5L31-32: Why (see previous comment)?

Reply similar to the previous one

22. P5L33: What are "eastern sects"?

Removed

23. P6L1: Provide references for this statement.

Added ; Page 7 lines 1-4

24. Why are low INP concentrations relevant? Are INP's used in any of the experiments?

Removed the sentence and modified Discussion section; Page 7

25. "temperatures between the homogeneous and the heterogeneous freezing points"; rewrite, it's unclear what is meant

Removed the sentence

26. P6L17: 0.5 x d is used above

Similar to comment 8

27. P6L19-20: Why are these then shown?

We have modified the Results and Discussion sections

28. P6L22: This is not discussed anywhere. Either a discussion is added or the respective experiment and its results should be removed.

Added details in Page 3 lines 12-33

29. P6L29-30: Is there an explanation why the capacitance change has no significant impact in the tropics?

In an earlier study by Furtado et al., 2016 (using the NWP model), it has been shown that for tropics and subtropics there is a general tendency by the model to overpredict the LWP in response to microphysics modifications. Increasing the stratiform cloud LWP will cause more SW radiation to be reflected back to space. But over the Southern Ocean, this effect is beneficial because the Unified

Model has a large negative bias in outgoing SW radiation in that region. Some possible reasons mentioned are that of flaws in parametrizations, uncertainities in the estimation of LWP in the convection scheme etc. Basically, in a frontal steady state, the capacitance doesn't have much of an impact compared to more dynamic sites like that of super cooled liquid water clouds. Further details can be found in Furtado et al., 2016.
Page 6 lines 11-19

30. P6L29-30: Why does the capacitance change not significantly change or even decrease SW CRE in the tropics? Is this model dependent?

For the first part of the comment, response similar to the previous point. For the second part, mostly it is not model dependent. Changes in capacitance can be translated to any model that uses that factor. Basically any model that is using capacitance change is a sink of water vapour. The impact of capacitance predominantly depends on the amount liquid water already available in the model. So, if some models have very less liquid water, then the impact of capacitance might not be much.

31. P7L9: There's no discussion why these temperature thresholds have been chosen for the sensitivity experiments. Are this thresholds considered to be realistic?

We have added more details in the text; Page 3 lines 20-22

32. P7L20-21: As these changes are not described in the literature or publicly accessible, they need to be described here.

Appendix modified

33. P7L25: The link is not publicly accessible.

As it is not a published version for the control, we have added some additions to its predecessor that are relevant to this study in the Appendix.

34. Table 1: The experiments could have more meaningful names which indicate what has been changed. Why is the all-ice temperature 1 deg C larger than the start-ice temperature?

We have renamed the experiment names for clarity. The 1 deg C change is merely technical to avoid division by zero in the code.

35. Fig. 1: the sensitivity experiments should be added to this figure. ERA5 is

a re-analysis dataset not an observational dataset.

We have removed this figure in the modified version

36. Fig. 3 and all similar figures: a vertical line at 0 Wm-2 is missing. Also these figures make it hard to compare different experiments. One panel should rather show anomalies for one variable but for all experiments and observations. Where do the sensible and latent heat observations come from?

We have included modified figures. Observational Data section 2.2 has also been modified to accommodate the changes.

37. Fig. S8b shows that exp2 still has a SW top-of-the-atmosphere (TOA) bias although no more ice is present in the mixed-phase temperature range. This indicates that the SW TOA bias is not only due to the wrong phase of mixed-phase clouds in GA7.1* but that there are biases also in other clouds.

We have removed this figure. New figures using observational data is used in the main text.

38. Fig. S8 shows that the SW TOA bias in the NH increases in exp1 compared to ctrl. Also from 50S to 60S the SW TOA bias increases in exp1 compared to ctrl. Is changing the capacitance really improving the agreement with observations? The rootmean-square error and correlation coefficient with respect to CERES would show if the experiments are an improvement globally.

We have now removed this figure. As we have now noted in the revised main text, change in capacitance is mostly favorable for the dynamic regions like super cooled liquid clouds (SO for instance). Since, the focus of our study is mainly SO, we have included fluxes and SW CRE plots (zonal) only for the SH. The global spatial plot is shown mostly for completeness and also as a motivation for the importance of INP and we have emphasized this is in the newer version.

Reviewer 2 comments

1 Summary

"However, the study has some issues involving justification of the experimental design, discussion of the simulations, and clarity of the figures and writing. If these issues are addressed, then the manuscript might be acceptable for publication. I therefore recommend major revision."

Manuscript modified as per comments below

2 Specific Points

1.Title : I think "improved" is not appropriate to use in the title since the authors did not improve the theory on which the cloud parameterizations are based. Changing the tuning parameters in a model, as the authors have done in this study, is not the same thing as improving the model. I suggest that the title be changed to something like "Bias of Southern Ocean cloud albedo in a general circulation model linked to ice-crystal shape."

Title modified

2.Abstract : All of the abstract is fine except for the last sentence. The last sentence should be removed because the authors did not do any new work to justify this statement ("We hypothesize that such abundant supercooled liquid cloud is the result of a paucity of ice nucleating particles in this part of the atmosphere."). It is unethical to make this statement in the abstract because the statement is based entirely on the work of others. It would be fine to include this statement in the discussion section with proper references, of course.

Modified

3. Data and Experimental Set-up: The experimental design needs to be explained and justified in more detail. For instance, the authors perform a sensi-

tivity study in which the ice-crystal shape is modified. This is done by multiplying the "capacitance" (C) value by a factor of 0.5, which effectively changes the ice-crystal shape from spheres to ellipsoids. However, the authors do not cite any theoretical or observational work to justify their choice of 0.5 until the Discussion section (pg. 6 line 8), and even there it is simply stated that the choice of C is reasonable without any explanation. More background information justifying the choice of C=0.5 is needed in Section 2.1. It would also be nice if the authors provided some justification for their choice that is based on in situ observations over the Southern Ocean, perhaps from the recent SOCRATES field campaign.

We have added some more information in Section 2.1 (Page 3 lines 5-8). Regarding in situ observations, we are not aware of any capacitance or aspect ratio of ice crystals related data from SOCRATES.

A second issue is that, as far as I can tell, some of the simulations and discussion are unrelated to the study goals. Simulations exp2 and exp3 use modified temperatures for ice nucleation in the convection and microphysics parameterizations. How do these experiments contribute to the goal of understanding how ice-crystal shape affects Southern Ocean cloud albedo?

We have added more details regarding this in Section 2.1 lines 5-29

Also, the control simulation is compared to older versions of the model with no explanation of how this comparison helps to understand the cause of the cloud albedo bias in the current model (pg. 5 line 20, Figure 6). I do not understand the value of exp2, exp3, or the older versions of the model presented in Figure 6. Please discuss this or remove the content.

We have now removed the comparison with earlier model versions

4. Results and Discussion

The Results section is hard to follow. It would help to organize the figures and text in a consistent way. The text discusses model bias in the TOA and surface energy budget terms one at a time, so it would be helpful if the data presented in Figure 3-5 were also organized based on different energy budget terms. For instance, Figure 3 could have one panel that shows LW TOA in ctrl, exp1, exp2, and exp3; another panel that shows SW TOA in ctrl, exp1, exp2, and exp3; and so on. Since model bias is the quantity of interest, it would also help to show all of the anomalies relative to observed values (e.g. ctrl – obs, exp1 – obs, exp2 – obs, exp3 – obs) rather than anomalies relative to the ctrl experiment in some of the panels and anomalies relative to observations in other panels.

We have added modified figures

Another issue is that the content of the Discussion section doesn't seem to logically follow from the content of the Results section. The Results section describes how the model biases change as a result of the modifications to the cloud parameterizations, which is fine. But no clear conclusion about what was learned from these simulations is reached in the Discussion section. Should other modeling groups change the ice crystal shape in their models? If so, what range of capacitance values is suggested by observations and theory, and what values do the authors recommend using? How much of the Southern Ocean cloud albedo bias will be fixed by changing the ice-crystal shape? Please make a clear statement about what was learned from your work before starting the discussion about how other studies say that ice-nucleating particles are the critical thing to study (pg. 6 line 31).

Modified the Results, Discussion and Conclusion sections to make our findings more clear

5. Technical Corrections
Figure 1 – Change axis label to "IWP (km/m2)" to match the rest of the text.

Removed the figure

Figure 2 – Why is the range of the x-axis so much larger in 2a-b than in 2c-d? Make the axis range consistent across all panels.

Modified

Figure 2 – I suggest moving all of the information about cloud types from the figure caption to the main text.

Added cloud type details in the main text; Page 4 lines 20-23

Figure 3,4 – Please organize the data so that one panel shows one energy budget term only, and that all anomalies are shown relative to observations, as mentioned in my comments on "Results and Discussion" above.

Modified figures added

Figure 6 – What value does this figure add to the study? I think this figure should be removed

This figure has been removed.

Figure 7 – What does this figure show that isn't already shown in Figure 5? It shows a big response in the tropical western Pacific to changing the nucleation temperature, but this isn't relevant to understanding Southern Ocean cloud albedo biases.

We have added more details in the results section explaining this.

Figure 6,7 – The colorbar makes these figures very difficult to read. Please change the colorbar to a two-color scale with white at zero. For example, the colorbar could have red for positive values, white for near-zero values, and blue for negative values.

Modified figure added

Pg. 1 line 19 "observed radiation biases" – delete "observed"

Deleted

Pg. 2 line 6 – specify that "this model problem" means cloud albedo bias over the Southern Ocean

Modified

Pg. 2 line 8 – I recommend moving the sentence "In the present study, we investigate. . ." to the end of the preceding paragraph and moving the sentence "Here, we define a SO. . ." to Section 2 Data and experimental set-up. I think it helps to finish the Introduction with a concise statement of the study goals, which is what the first sentence does.

Modified; Page 2 lines 7-10

Pg. 2 line 12 – Why isn't this paragraph in section 2.1 Model set-up?

We have added few more background details in the UM model version in the Appendix.

Pg. 2 line 13 – Is it necessary to put the model description in an appendix? Appendix A is only one paragraph long, after all. It improves the clarity of the paper if the reader doesn't have to jump around between different sections.

We have modified Section 2. Appendix is included with more details now as these are not publicly accessible yet due to licensing issue.

Pg. 3 line 14 "parametrised convection scheme" – "parametrised" is redundant and can be deleted.

Modified

Pg. 4 line 8 – Why does modifying the capacitance value affect liquid and ice? Does the capacitance value control the diffusional growth of liquid droplets as well? If so, then I don't think that C=0.5 is realistic for liquid droplets. Also, why does changing the ice nucleation temperature predominantly affect IWP? I think other studies suggest that it should affect both LWP and IWP [e.g. Kay et al., 2016].

The effect of capacitance on liquid is mostly indirect. When ice grows slower, it leaves more water vapor around to condense to liquid drops. And if the capacitance is high, then ice crystals grow faster and there is less liquid. So, by making the capacitance value to 0.5 from the default value of 1.0, we are in a way reducing the depositional growth of ice crystals, leaving more room for water vapor to condense (e.g.Wegener, 1911; Bergeron, 1935; Findeisen : same also provided in the main text reference). Kay et al., 2016 shows the improvement in radiation biases over SO by modifying the shallow convection temperature rather than tuning the cloud microphysics.

Pg. 4 line 11, Pg. 5 line 9, Pg. 5 line 19 – Please don't just state that these figures are included in the supporting information. You need to say what the figures show and how they contribute to the findings of the study.

We have modified the Supplementary section and its reference in the main text. Page 4 lines 22-24

Pg. 4 line 17 – Why is the change in TOA LW flux so large in your simulations? LW radiation was not part of the motivation, yet TOA LW flux is more sensitive than TOA SW flux to the model modifications made in this study. Please explain this.

For the atmosphere only version of the model (i.e. without any interactive sea surface temperature), the LW changes are slightly complicated because any changes in the radiation budget of the SW does not have any impact on the outgoing radiation from the sea-surface. But the changes that we see here in the LW could be mostly due to the changes associated with the amount of cloud cover and cloud height that we observe in the experiments. When there is more horizontal cloud cover then more of the surface is covered and that will have an impact on the LW distribution. Also, when the cloud height changes i.e when it becomes thicker that could also impact the LW. We have now emphasized in the discussion/conclusions sections that the capacitance changes are aimed mostly at the boundary layer clouds and nucleation temperature changes could also influence the high clouds. We have also now made it more clear that it is the SW flux that is mostly benefiting and also mention about the detrimental effects on other fluxes.
Page 6 lines 20-25

Pg. 4 line 22 – By "show an increase" do you mean an increase relative to the control experiment? Please clarify.

We have modified the Results section.

Pg. 5 line 1 – It would help to discuss the difference between the control simulation and observations first to establish the baseline model bias, then discuss how the bias changes in exp1-3. Please rearrange content accordingly.

Modified

Pg. 6 line 18 "The atmosphere-only model studied here does perform better. . ." – Please use more specific language. For example, "model bias in SW CRE is reduced over the Southern Ocean."

Modified

Reducing the Southern Ocean cloud albedo biases in a general circulation model

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Abstract. The present generation of global climate models is characterized by insufficient reflection of short-wave radiation over the Southern Ocean due to a misrepresentation of clouds. This is a significant concern as it leads to excessive heating of the ocean surface, sea surface temperature biases, and subsequent problems with atmospheric dynamics. In this study we modify cloud micro-physics in a recent version of the Met Office's Unified Model and show that choosing a more realistic value for the shape parameter of atmospheric ice-crystals, in better agreement with theory and observations, benefits the simulation of short-wave radiation. In the model, for calculating the growth rate of ice crystals through deposition, the default assumption is that all ice particles are spherical in shape. We modify this assumption to effectively allow for oblique shapes or aggregates of ice crystals. Along with modified ice nucleation temperatures, we achieve a reduction in the annual-mean short-wave cloud radiative effect over the Southern Ocean by up to $\sim$4 Wm^{-2}, and seasonally much larger reductions. By slowing the growth of the ice phase, the model simulates substantially more supercooled liquid cloud. ~~We hypothesize that such abundant supercooled liquid cloud is the result of a paucity of ice nucleating particles in this part of the atmosphere.~~

1 Introduction

One of the major known ~~drawbacks in the~~ problems in present-day global climate models is an excess in the absorbed short-wave (SW) radiation over the Southern Ocean (SO) ~~(Trenberth and Fasullo, 2010; Ceppi et al., 2012; Hwang and Frierson, 2013; Hyder et~~ ~~. In~~ (Trenberth and Fasullo, 2010; Ceppi et al., 2012; Hwang and Frierson, 2013; Williams et al., 2013; Hyder et al., 2018). Chapter 9 of the 5$^{\text{th}}$ Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR5) (Flato et al., 2014) ~~, it~~ points out that most of the 5$^{\text{th}}$ Coupled Model Intercomparison Project (CMIP5) models (Taylor et al., 2012) have a positive SW cloud radiative bias of magnitude of up to 20 Wm^{-2} over the SO, suggesting that inadequately simulated clouds allow substantially too much sunlight to reach the ocean surface.

Several studies have focused on the relation between various aspects of cloud representation in the model and ~~observed radiation biases~~ radiation biases pronounced over the SO. Bodas-Salcedo et al. (2012, 2014), using cyclone compositing cluster analyses, suggest the need to increase the optical depth of the low-level clouds and improve the simulation of mid-level cloud regime, to help reduce the biases in the model. By modifying the shallow convection detrainment in their global climate model, Kay et al. (2016) showed that the resultant increase in the supercooled liquid clouds (SLC) enable large reductions in long-standing climate model SW radiation biases. ~~By implementing a new parametrisation that includes the turbulent production~~ Furtado et al. (2016) and Lohmann and Neubauer (2018) point towards the significance of mixed-phase ~~clouds, Furtado et al. (2016) show that the radiation biases can be substantially improved, especially over the~~ cloud and their representation in the models for better representation of SO. In another study by Furtado and Field (2017), the importance of ice micro-physics parametrisation in determining the phase composition, and thus the liquid water content of the SO clouds is highlighted.

Discrepancies in the response of clouds to anthropogenic forcings are recognized as a leading reason for a persistent, large spread in the climate sensitivity throughout various generations of climate models (Allen et al., 2014). We thus conjecture that this model problem of cloud albedo bias over the SO contributes to this large spread, and thus solving it would increase confidence in projections of anthropogenic climate change (Tan et al., 2016).

In the present study, we investigate the role of parameters involved in atmospheric ice formation within a global climate model in causing the above mentioned SW radiation bias. ~~Here, we~~

2 Data and experimental set-up

We define a SO region as the latitudinal band between 50°S and 70°S ~~.~~

3 ~~Data and experimental set-up~~

in this study. The control climate model used in this study is ~~an accrual of~~ the most recent version of the Met Office's Unified Model, GA7.1 (Walters et al., 2019) with modified micro-physics scheme for riming process and several other scientific changes. Appendix A summarizes the scientific set-up for this model version. The resolution used here is N96L85 (i.e. a horizontal resolution of $1.875° \times 1.25°$ and 85 terrain-following hybrid-height levels extending to 85 km of altitude). It uses the "ENDGAME" dynamical core with a semi-implicit semi-Lagrangian formulation to solve the non-hydrostatic, fully compressible deep-atmosphere equations of motion (Wood et al., 2014)

2.1 Model set-up

~~In the present study,~~ The control run follows the Atmospheric Model Intercomparison Project (AMIP) climate model development protocol ~~(Gates et al., 1999; Schuddeboom et al., 2019)~~(Gates et al., 1999), using prescribed ~~sea-surface temperature climatology~~ Reynolds sea surface temperature climatology covering 1981-2012 (Reynolds et al., 2007). Excess atmospheric ice has been a persistent concern in the control version of the model~~(fig. ??)~~, which is especially pronounced over the SO region. Ice clouds have a significant influence on the global climate through their effects on the Earth's radiation budget e.g. (Hartmann and Doelling, 1991; Waliser et al., 2009). Hence, sensitivity set-ups in our study are aimed at modifications to the micro-physics scheme such that the ice growth in the model is controlled. We achieve this by modifying those parameters that control the growth of existing ice by vapor deposition and heterogeneous nucleation of new ice. The classical theory of ice crystal growth uses an electrostatic analogy due to the similarity between the equations governing the water vapor distribution around an ice crystal and the electrostatic potential distribution around an electric conductor of the same shape as the ice crystal (Chiruta and Wang, 2003). Thus, the growth rate of ice crystals by diffusion depends on a shape (also known as capacitance) parameter C, which is a function of both ice crystal size and habit. To determine the ice crystal growth rates in models, it is necessary to know the value of C (Chiruta and Wang, 2003; Hobbs, 1976). The standard equation that is used for calculating the growth rate of ice crystals in the model is,

$$\frac{dm}{dt} = 4\pi D_v C \left(\rho_{\alpha s} - \rho_{s\alpha}\right) \quad (1)$$

where ~~D_v is the diffusivity of water vapor in air,~~ C is the capacitance, ρ_α and ρ_s are distributions of vapor densities at and away from crystal's surface (Houghton, 1950).

From eq.1, it is evident that once the value of capacitance C is known, the growth rate of ice crystals can be determined. All other quantities on the right-hand side of eq.1 are independent of the shape (Chiruta and Wang, 2003; Hobbs, 1976). Thus, C in the model effectively defines the shape of ice crystals, which in turn is fed ~~through~~ to the ice processes of deposition/sublimation and melting without affecting any other ice processes.

Technically the capacitance, C, is defined as 1.0 x d in the model ~~,~~ where d is the particle maximum size. ~~In~~ However, studies have suggested that this value overestimates the evaporation rate of snowflakes by a factor of 2 (Westbrook et al., 2008) . It has been shown in other studies based on theory and observations that by changing the value to 0.5 x d, models show a significant improvement compared to the traditional approximations used (Westbrook et al., 2008; Field et al., 2008) . Thus, in our sensitivity studies, we modified the value to 0.5 x d (corresponding to any oblate ellipsoid with two unequal axes, thought to be more appropriate for aggregates and plate-like crystals rather than the assumption of spherical crystals alone). ~~Our value of 1.0 or 0.5 is a non-dimensional capacitance (Field et al., 2008).~~ The effect of this change in the shape parameter is tested independently as well as in combination with changing the temperatures at which heterogeneous and homogeneous freezing start in the cloud micro-physics scheme. The idea behind modifying the nucleation temperatures is to test the behaviour of capacitance change in a relatively cleaner environment. Basically, the ice nucleation temperature is the temperature at which heterogeneous nucleation of ice first starts to occur in the model. In the control model, this is solely following the temperature dependent function suggested by (Fletcher, 1962). The default value ~~of~~ in the model is $-10°$C for heterogeneous nucleation temperature. However, in much cleaner environments, like the SO, ice nucleation might not start at $-10°$C as there is a paucity in the ice nucleating particles (INPs). Hence, in reality the nucleation temperatures are much colder for these regions. Since we don't have any INP dependency taken into account for ice nucleation temperature in the control model, to test the behaviour of capacitance in such conditions, experiments are conducted by changing the default value of $-10°$C ~~was changed~~ to $-40°$C and $-20°$C~~, to investigate the effect of delaying the heterogeneous ice~~ . The higher threshold of $-40°$C has been chosen as it is the maximum temperature at which homogeneous nucleation occurs in the model (i.e. at this temperature all liquid is instantaneously frozen to form ice particles, (Yau and Rogers, 1996)). Along with the nucleation temperature in the micro-physics scheme, convection scheme also impacts the amount of ice produced in the model through its detrainment temperatures. We thus further modified the convection scheme by changing the detrainment temperatures to be very cold from the default values. This thus gives us an overall base to investigate the effect of delaying the heterogeneous ice nucleation in the model~~. Two further parameters that were modified in the parametrised convection scheme that control ice formation in the model are the~~ . The temperature at which the detraining condensate as ice begins in the model ~~(~~is the start-ice temperature ~~)~~ and the temperature at which all condensate is detrained as ice ~~(~~is called the all-ice temperature~~).~~ . Thus, we conducted three sensitivity experiments (henceforth referred to as *cap*, *c_tnuc=-40*, and *c_tnuc=-20)* to be compared against the control run. The values used in our numerical simulations are summarised in Table 1.

~~The ice nucleation temperature is meant to be similar both in large-scale and convective cloud schemes. Hence,~~ We note that the experiment where ~~the~~ nucleation temperature is ~~reduced~~ modified to -40°C (i.e. ~~exp2) is physically unrealistic~~*c_tnuc=-40)* is applicable mostly for cleaner environments like the SO but not physically realistic for rest of the world, as mentioned in the previous paragraph. However, it is still a much useful sensitivity scenario to study the importance of detrained ice vs. large-scale freezing. All simulations were run for twenty years under steady-state present-day conditions.

2.2 Observational data

We use the National Aeronautics and Space Administration (NASA) Clouds and the Earth's Radiant Energy System - Energy Balanced And Filled (CERES EBAF Ed4.0, Terra-Aqua) ~~surface and~~ for comparing incoming surface long-wave (LW) and short-wave (SW) as well as the top-of-the-atmosphere (TOA) ~~data set,~~ radiation covering the period 2000 to ~~2018 as an observational reference for radiative fluxes.~~ 2018. This data set, in an earlier version, (Loeb et al., 2009), was ~~also~~ used in AR5. The overall uncertainty in the monthly all-sky TOA flux for the CERES EBAF Ed4.0 data set is estimated to be 2.5 Wm^{-2} (for for both SW and LW fluxes). For clear-sky TOA, uncertainties in SW and LW fluxes are 5 Wm^{-2} and 4.5 Wm^{-2} respectively (Loeb et al., 2018). ~~We also use the European Centre for Medium-Range Weather Forecasts (ECMWF)Re-Analysis 5 (ERA5) monthly mean data for comparison of cloud-ice content (ERA5, 2017).~~ Direct observations of ocean surface air-sea fluxes are extremely sparse, particularly over the Southern Ocean. There are large uncertainties in the conventional observational surface heat estimates which can affect the evaluation of simulated surface energy budgets. Hence, for the net surface flux comparison, we are using a combination of both TOA fluxes from satellite and ERA-Interim reanalysis energy divergences (assuming atmospheric column energy conservation). This approach considerably constraints the estimates of net surface flux derived from re-analyses. Further details regarding this approach can be found in (Hyder et al., 2018).

3 Results

~~Fig.??~~ FigureA represents the anomaly in the annual and DJF mean distributions of ice water path (IWP) and liquid water path (LWP) for stratocumulus boundary layer clouds in the model in various experiments with respect to the control run, for the Southern Hemisphere (SH). ~~The~~ There are seven boundary layer types that have been identified in the model based on the surface stability and capping cloud (Lock et al., 2000). ~~Further information on the types of boundary layers considered is included in the figure caption.~~ As our focus is mostly on the stratocumulus boundary layer type clouds in this study, the cloud types considered in this figure are: type 2 = boundary layer with stratocumulus over a stable near-surface layer, type

3 = well-mixed boundary layer and type 4 = unstable boundary layer with a decoupled stratocumulus (DSC) layer not over cumulus. The IWP and LWP are calculated collectively over these types. The other cloud types in the model are those of stable boundary layer (type=1), boundary layer with de-coupled stratocumulus layer over cumulus (type=5), cumulus-capped boundary layer (type=6) and shear-dominated unstable layer (type=7). A similar analysis for the non-stratocumulus cloud types has been provided in the Supplementary material (Figs. S1 and S2) for annual and DJF means.

From ~~fig. (??a)~~ Figs. (Aa) and (Ab), it is evident that there is noticeable decrease in the ~~annual-mean~~ IWP in the stratocumulus boundary layer clouds as a result of modified micro-physics, which is captured in all sensitivity experiments ~~. Exp2~~ in both annual and DJF means. The experiment, *c_tnuc=-40* (solid black line in ~~fig. ??a~~ Figs. Aa and Ab) shows the maximum response and ~~exp1~~ the experiment *cap* (solid red line ~~fig. ??a~~ Figs. Aa and Ab) has the minimum decrease in IWP with respect to the control run. ~~This response pattern is similar for DJF mean as well (fig. ??b).~~ Conforming to the decrease in the IWP, there is a corresponding increase in the LWP as well, over the SO region (~~figs. ??c and ??~~Figs. Ac and Ad). However, the response of LWP is more or less similar in all the 3 experiments ~~w.r.t~~ with respect to the control run. It is because modification to capacitance value affects both the liquid and ice water contents while changes to nucleation temperature will have an impact predominantly on ~~ice water path.~~ IWP. The zonal mean LWPs as shown in Fig. (A) are mostly dominated by the fronts. So, even if the changes to nucleation temperature shows some sensitivity, they are mostly away from the frontal systems and hence will be mostly restricted to the shallow boundary layer types thus not impacting the LWP much. Thus, experiments where both capacitance and nucleation temperature are modified will have an added impact on the IWP.

~~Zonally averaged distribution of IWP and LWP, over both hemispheres, for all boundary layer types for annual and seasonal means are provided in the supplementary material (figs. S1 to S4).~~

Figure 2 shows the zonal-mean changes in the annual-mean distributions of various radiative fluxes in the model for the SH. In all the model experiments there is a general decrease in the outgoing ~~long-wave (LW)~~ LW flux at the ~~top-of-the-atmosphere (TOA)~~ TOA in the SO region (solid ~~red line in figs~~lines in Fig. 2a~~to 2e~~) with respect to the control run. This is accompanied by a corresponding increase in the outgoing SW flux at the TOA (~~solid black line in figs. 2a to 2e~~dotted lines in Fig. 2b), indicating that in all experiments the planetary albedo has increased versus the control. Except in ~~exp1 (i.e. fig. 2a)~~*cap*, the decrease in LW radiation at the TOA, in absolute terms, is larger than the increase in SW TOA over the SO. This is visible in the distribution of net radiation at the TOA (i.e. LW plus SW at TOA) ~~as well (solid mustard lines in figs. 2a to 2~~(dashed red line in Fig. 2c). For ~~exp1~~*cap* experiment, there is an increase in the net outgoing TOA radiation whereas for ~~exp2 and exp3~~*c_tnuc=-40* and *c_tnuc=-20* experiments, it shows a decrease over the SO region.

The surface distributions of the radiative fluxes are represented ~~by solid magenta, gray and blue lines in figs. 2a to 2e~~in Figs. 2d to 2f. In all the experiments, the net downward LW radiation at the surface shows an increase over the SO (solid ~~magenta lines)~~lines in Fig. 2d) with respect to the control run. The corresponding SW component shows a decrease over SO (~~solid gray lines). The net radiation at surface (i.e. downward LW plus SW at surface)shows a general decrease in all experiments over SO (solid blue lines)~~dotted lines in Fig. 2e). The distribution of anomaly in the radiative heat ~~flux~~ fluxes with respect to the control run is represented by ~~solid cyan line in figs. 2a to 2e~~dashed lines in Fig 2f. It primarily represents the difference between total net downward surface radiation and total heat flux at the surface i.e (incoming LW + SW at surface) - (sensible heat flux ~~, SH~~ + latent heat flux~~, LH~~). Although there is an improvement (i.e. reduction) in the downward SW component (~~solid gray lines~~ dotted lines in Fig 2e), due to the compensating increase in the LW component (solid ~~magenta~~lines in Fig 2d), there is a net increase in the heat flux into the surface over the SO (~~solid cyan lines~~ dashed lines in Fig 2f) in almost all experiments. However, the net radiative heat flux shows a tendency of slight decrease over SO for ~~exp1 w.r.t~~ *cap* experiment with respect to the control run (~~solid cyan~~ dashed green line in fig. 2~~a~~f).

Figure 3 shows the distributions of various radiative fluxes in the model for the SH for the DJF season. ~~As expected, the~~ The radiative fluxes show a more pronounced response during the austral summer season. The net radiative flux at TOA (~~solid mustard lines~~ dashed lines in Fig. 3c) is showing an increase over the SO for all the experiments unlike the annual-mean distribution where only the ~~exp1~~ *cap* experiment showed an increase. Similarly, the net radiative heat flux at the surface (~~solid cyan lines~~ dashed lines in Fig. 3f) shows a general decrease over the SO in all the experiments ~~w.r.t~~ with respect to the control run for the DJF season~~whereas~~ . Whereas in annual-mean, only ~~exp1~~ *cap* experiment showed a decrease ~~.~~ in net surface flux.

~~The dashed lines in fig. 2d represent~~

Figure 4 represents the difference between the ~~observational data and model control data~~ model experiments and observational data for annual-mean. It is mainly intended to provide a reference for the model behaviour in terms of radiative fluxes. ~~The surface radiative fluxes in the model (dashed magenta, gray, blue and cyan lines) are generally in better agreement with the observations than those at the TOA (dashed red, black and mustard lines), especially over the SO region. Although the SW TOA flux (dashed black line) is mostly in agreement between model and observational data, the disparities in LW TOA equivalent (dashed red line) are noticeable in the net radiative flux at surface well (dashed mustard). The dashed lines in fig. 3d , represent the observational data reference for the DJF season. Relative to the annual-mean, the model and observational data are more comparable in terms of the~~ By comparing Figs. 2 and 4, it can be seen that it is the LW component that shows similar signs of response (solid lines in Figs. 2a, 2d and 4a, 4d) than SW for SO region. But the net fluxes show mostly similar signs of response in ~~the DJF season. Global zonal plot for annual and seasonal mean distribution of radiative fluxes are provided in the Supplementary material (figs. S5 to S7). Supplementary material also includes the anomaly of all model experiments w.r.t the observational data as well, i.e. model experiments - observational data (figs. S8 to S10~~both TOA and surface in Figs. 2c, 4c and 2f, 4f except for the TOA flux in *cap* experiment (dashed red line in Fig. 2c).

Figure ~~?? shows the zonal averaged distribution of~~ 5 shows the zonally averaged annual and DJF mean distributions of the anomaly in the SW cloud radiative effect (SW CRE) between different model ~~runs~~ experiments with respect to the control run. The SW CRE shows the impact of cloud on TOA SW flux and is calculated by ~~differencing the upwelling SW radiation in~~ taking the anomaly of TOA SW flux between the cloudy and non-cloudy ~~conditions (Ramanathan et al., 1989; Allen et al., 2014).~~ grid boxes. The reduction in the SW radiative flux over SO is more pronounced in the DJF season (Fig. 5b) with *c_tnuc=-40* experiment showing the minimum reduction in SW CRE compared to the control run.

Figure 6 shows the annual and DJF mean spatial distributions of the anomaly in SW CRE between different model experiments with respect to the control run. It is evident from Fig. 6 that there is ~~significant~~ a general improvement (i.e. a reduction) in the SW CRE over the SO ~~regions~~ region in all three experiments compared to the control run. The reduction ~~in the SW radiative flux over SO~~ is more pronounced in the ~~DJF season (fig. ??b). For both annual and DJF means, both exp1 and exp3 (solid red~~

~~and yellow lines in ??a and b)show a stronger reduction in SW CRE over the SO region than exp2 (solid black line)compared to the control run.~~

~~The zonal SW CRE for austral winter season is provided in the supplementary material (fig. S11).~~

cap experiment (Figs. 6a and 6d). The response in *c_tnuc=-40* is the minimum (Figs. 6b and 6e). As expected, the response is more robust for the DJF season in all experiments with respect to the control run (Figs. 6d to Fig. 6f).

~~Figure ?? shows the evolution of SW CRE improvement over SO in various versions of the UM.~~

Figure 7 shows the spatial distribution of TOA SW CRE anomaly between various model simulations with respect to the CERES TOA data. As evident from Fig. 7a, the control model does have an excess in the absorbed SW radiation over the SH high latitudes like many other global models. Comparing Fig. 7a with the Figs. ~~??aand ??b show the anomaly in the SW CRE in the previous model versions of GA6 (Walters et al., 2017) and GA7 (Walters et al., 2019) w. r. t that of the CERES EBAF observational data. As evident, there has been significant improvements of the SO radiation biases in GA7 compared to its predecessor GA6. One of the major reasons behind this improvement was a better representation of mixed-phase clouds and supercooled liquid in the cloud~~ 7b to 7d, it can be seen that the changes in micro-physics ~~scheme (Furtado et al., 2016).Fig. ??c shows~~ parametrisation have improved (i.e. reduced) the SW CRE ~~comparison of the current control model version, with that of the observational data~~over the SO. In general there is an increase in the reflected SW radiation ~~in the current control model version compared to GA7. While this has benefited regions like equatorial precincts of Indian, western Pacific, North Atlantic and obviously the SO, it also has some adverse impact on regions like equatorial eastern Pacific, South Atlantic etc. However, sectors like the Bay of Bengal, South China Sea etc still have biases just like in the previous modelversions~~over the SO compared to the control model.

~~Figures ??a to ??c show~~ It is to be noted that the tropical regions don't show much reduction in the SW CRE ~~anomaly in various experiments used in this study w.r.t that of the control run. As expected, all the experiments show a decrease in the SW CRE compared~~ in response to the capacitance changes. While the SO does show significant reduction in SW CRE with respect to the control run~~over the SO region. As already shown in fig. ??a , the reduction of SW CRE over SO is most pronounced for exp1~~ , especially for the *cap* experiment (Figs. 6a and 6d), the tropical regions still show an increase. In an earlier study by (Furtado et al., 2016), using a similar version of the control model (Numerical Weather Prediction NWP configuration), it has been shown that for tropics and subtropics there is a general tendency by the model to overpredict the LWP in response to microphysics modifications. Increasing the stratiform cloud LWP will cause more SW radiation to be reflected back to space. But over the SO, this effect is beneficial because the control model already has a large negative bias in outgoing SW radiation in that region. Some potential reasons could be the flaws in parametrizations or uncertainities in the estimation of LWP in the convection scheme. Basically, in a frontal steady state, the capacitance does not have much of an impact compared to more dynamic sites like that of supercooled liquid clouds.

Generally, the impact of ice nucleation temperature experiments (*c_tnuc=-40* and ~~exp3 followed by exp2. For exp1 (capacitance only), there is an increase in the SW CRE over regions like eastern Australia, South China Sea, eastern sects of South America etc. For exp2 and exp3, equatorial western Pacific shows much sensitivity in terms a reduced SW CRE compared to the control run.~~ *c_tnuc=-20*) on fluxes is more mixed than using capacitance change alone (*cap*). The detrimental effects due to changes in the ice nucleation temperature could be mostly attributed to the changes in the vertical distribution of clouds affecting not just the low clouds but also the high clouds. By changing the nucleation temperature, essentially the level at which freezing occurs is modified. When the freezing of water in lower levels is delayed it results in cirrus clouds at higher atmospheric levels. This can change the high cloud characteristics thus affecting both LW and SW.

4 Discussion

~~An overestimation of ice in clouds is a known shortcoming of~~ Errors in the representation of ice clouds is one of the major shortcomings in many of the present-day global climate models ~~(fig. ??).~~ and this can have a significant influence on the global climate through their effects on the Earth's radiation budget (Hartmann and Doelling, 1991; Waliser et al., 2009). It is coupled to an underestimation of ~~SLC~~SLCs. This problem is of particular importance in the SO region characterized by abundant SLCs (Kay et al., 2016; Bodas-Salcedo et al., 2016; Huang et al., 2012; Hu et al., 2010). When ice and supercooled liquid coexist, the ice grows at the expense of the liquid by the Wegener-Bergeron-Findeisen (WBF) mechanism (Wegener, 1911; Bergeron, 1935; Findeisen, 1938). Acknowledging the complexities in representing the many possible background micro-physical processes that are responsible for this in a global climate model, the primary idea of modifying the shape parameter of ice-crystals is to reduce the rate of depositional growth of ice particles. This reduction essentially slows down the deposition growth of ice crystals, which leaves more water vapor to be available for condensation into liquid phase particles. ~~At the scale represented in global climate models, for conditions of very low ice-nucleating particle (INP) concentrations and temperatures between the homogeneous and the heterogeneous freezing points, this essentially amounts to a limitation of the speed of glaciation as freezing of SLCs can only occur at the interfaces of these two states.~~ By lowering the value of capacitance to 0.5 x d, we model a decrease in the IWP and an associated increase in the LWP over the SO region (~~fig. ??~~Fig. A). As a result of this increase in LWP, the outgoing SW fluxes are increased (~~solid black lines in figs. 2and 3~~dotted lines in Figs. 2b and 3b), i.e. an increased LWP corresponds to brighter clouds reflecting more sunlight. This results in a decrease of the downwelling short-wave radiation reaching the surface~~(solid gray lines in figs. 2 and 3).~~ .

Our choice of ~~$0.5 * d$ (d being the particle maximum size)~~ 0.5 x d for capacitance is based on theory and observational studies ~~(Field et al., 2008). The atmosphere-only model studied here does perform better~~ (Field et al., 2008; Westbrook et al., 2008). The control model has improved in terms of SO cloud albedo bias with this value than with the default value of ~~$1.0 * d$. The SW radiation over SO is improved but results are more mixed for the other fluxes (figs. 2 and 3). The uncertainty in the surface radiation budget observations also needs to be considered.As already noted earlier, the experiment where the nucleation temperature is reduced to -40°C (i.e exp2) is physically unrealistic and is intended to be a useful sensitivity scenario to study the importance of detrained ice vs. large-scale freezing.~~

~~Even though there is noticeable reduction in the SW radiation bias over the SO in all the experimental scenarios (fig. ??), we recognize persisting shortcomings in this regard in other parts of the world (figs. ??c. Similar to the control version in this study, certain regions have not shown much of an improvementin terms of the SW CRE bias (e. g. the Bay of Bengal, areas around southeast Asia, eastern south Pacific etc). Previous studies~~ 1.0 x d. However, as seen in Fig.7, even though the SO has shown signs of improvement, biases still remain especially in the tropics and other frontal steady states. Previous studies using a similar NWP configuration of the control model have suggested that some cloud micro-physics parameterisations produce unrealistically bright clouds, especially over the Northern Hemisphere (NH) (Furtado et al., 2016). ~~Since~~ In our control model, the SW biases over the NH were smaller than those over the SO ~~, a significant~~ and further brightening of modelled NH clouds is undesirable (Furtado et al., 2016). While the changes to nucleation temperature has significant impact on the tropics as well, the capacitance changes are more localized to the high latitudes.

~~Several~~ Our study shows that while modifying the capacitance is clearly benefiting the SO region SW radiative fluxes, there is some detrimental behaviour of fluxes due to the impact of ice nucleation temperature modifications. While an in-depth analyses is beyond the scope of this particular study, it is a significant aspect and provides an interesting outlook for future studies.

Also, several recent studies point towards the significance of INP for cloud phase (Kanji et al., 2017; Vergara-Temprado et al., 2018). A further development of the research outlined here could be to make glaciation explicitly dependent on INP concentration to attend to the persisting model biases in other regions of the world as well. At present, in most global climate models, cloud phase is determined only by a threshold temperature like in our control model. Vergara-Temprado et al. (2018), using a high-resolution numerical weather prediction NWP model and making assumptions on the INP concentration over the SO, simulate clouds that are ~~for~~ far more reflective than those in current global climate models, in better agreement with satellite observations.

5 Conclusions

In this study we ~~improve~~ reduce the SW radiation biases over SO in a recent version of the UK Met Office's Unified Model. This and other contemporary climate models are characterized by excess cloud ice causing biases in SW radiation ~~biases~~ which are especially pronounced over the SO. Here, we modify the capacitance or shape parameter which represents ice crystal shape and habit. In our sensitivity studies, we reduce this parameter from ~~1~~ 1.0 x d to 0.5 x d (corresponding to any oblate sphere shape in general, where the horizontal axes are longer than the vertical axis and more representative of an aggregate or flat ice crystal) ~~.~~ and thus delaying the depositional growth of ice particles. This leads to an increase in liquid water in stratiform clouds and consequently increases the outgoing SW over the SO. We also examine the impact of changing other temperature thresholds in the cloud micro-physics scheme for the onset of heterogeneous ice production. Our analysis shows that the SW radiation bias has significantly reduced over the SO after the modification of these parameters. However, disparities still exist in other regions. INPs that are currently not represented in the cloud micro-physics scheme might be a factor in this model behavior. The fact that nucleation temperature changes currently is associated with the same effects globally is undesirable, it further motivates the future work to couple the nucleation temperature to a prognostic or the least a regionally specified INP concentration.

Data availability. Model data is available at: http://doi.org/10.5281/zenodo.3775170.

Observational data is available at: https://ceres.larc.nasa.gov/order_data.php and

Appendix A

Several changes were introduced in the ~~GA7.1*~~ control model used in this study relative to its predecessor GA7.1 (Walters et al., 2019; Brown et al., 2012). These changes range from minor bug fixes and optimisation techniques to major science changes in the convection, large-scale-precipitation, boundary layer and radiation schemes. As far as our study is concerned, the main modification to GA7.1 is the inclusion of the modified micro-physics scheme which includes a shape dependence of riming rates using the parameterization by Heymsfield and Miloshevich (2003), as a measure to prevent small liquid droplets from riming (Furtado and Field, 2017). ~~The reference link to the control model with all scientific/technical details is documented in a Met Office internal repository ticket: GA7.1#256 . A brief description of scientific changes between various model versions can also be found in (Bodas-Salcedo et al., 2019)~~

Some of the modifications in the convection scheme include that of a prognostic based convective entrainment rate, implementation of a new melting scheme to remove larger spikes in convective heating in the mid-troposphere, a revised forced detrainment calculation and a corrected evaporation of convective precipitation to remove existing errors.

The modified boundary layer scheme also includes changes to reduce vertical resolution sensitivity and an improved turbulent kinetic energy diagnostic and how it is used for aerosol activation.

The change in the radiation scheme is the implementation of spectral dispersion suggested by Liu et al. (2008) to improve the simulation of the first aerosol indirect effect.

A brief overview of the science changes is available in the Unified Model Newsletter Dec 2017 edition (Research and Model Development News, pages 10 -12. This document is included along with the model data at: http://doi.org/10.5281/zenodo.3775170).

Author contributions. VV carried out the model runs, performed analysis, created figures, wrote the manuscript and was also involved in the design and conceptualization of the study. OM was involved with obtaining the project grant, supervised the study and analyses of results. PF, KF and PH provided guidance in designing the model runs and analyses of results. JW provided technical support in setting up global climate model in super-computer environment. All authors have read and approved the final paper.

Competing interests. The authors declare that they have no conflict of interest.

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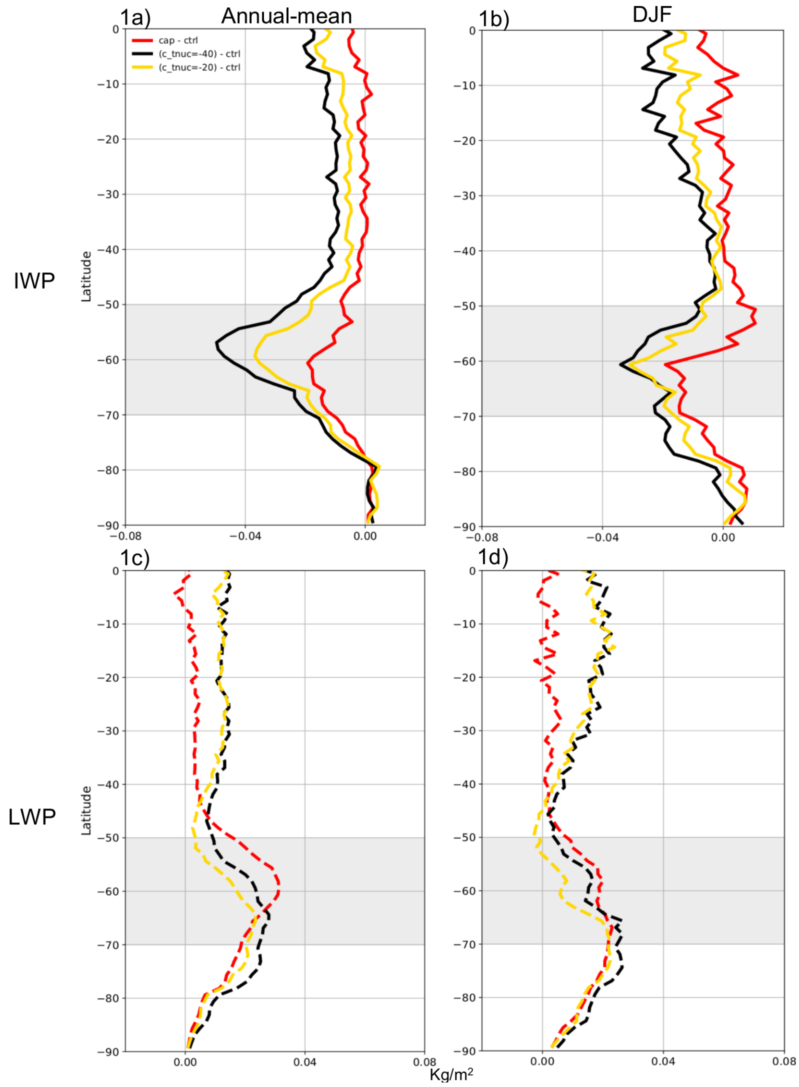
Table 1. Values used in the model runs

	Capacitance	Ice nucleation temperature (°C)	Start-ice temperature (°C)	All-ice temperature (°C)
control	1.0	-10	-10	-20
~~exp1~~cap	0.5	-10	-10	-20
~~exp2~~c_tnuc=-40	0.5	-40	-40	-41
~~exp3~~c_tnuc=-20	0.5	-20	-40	-41



Distribution of zonally averaged anomalies in IWP (solid lines in ~~2a~~ 1a and ~~2b~~1b) and LWP (dashed lines in ~~2c~~ 1c and ~~2d~~1d) over the stratocumulus boundary layer type clouds in the model for the SH. ~~The cloud types considered in the model are: type 2 = boundary layer with stratocumulus over a stable near-surface layer, type 3 = well-mixed boundary layer and type 4 = unstable boundary layer with a decoupled stratocumulus~~ (~~DSC~~1a) ~~layer not over cumulus. The IWP~~ and ~~LWP are calculated collectively over these types.~~ (~~2a~~1c) ~~and (2c)~~ represent annual-mean; (~~2b~~1b) and (~~2d~~1d) represent DJF mean. The colour codes are as follows: red = anomaly of ~~exp1~~ *cap* with respect to control, black = anomaly of ~~exp2~~ *c_tnuc=-40* with respect to control, yellow = anomaly of ~~exp3~~ *c_tnuc=-20* with respect to control. Values are calculated from 12 hourly instantaneous model output over 20 years. The SO region identified in this study is highlighted in gray.

Distribution of zonally averaged anomalies in IWP (solid lines in ~~2a~~ 1a and ~~2b~~1b) and LWP (dashed lines in ~~2c~~ 1c and ~~2d~~1d) over the stratocumulus boundary layer type clouds in the model for the SH. ~~The cloud types considered in the model are: type 2 = boundary layer with stratocumulus over a stable near-surface layer, type 3 = well-mixed boundary layer and type 4 = unstable boundary layer with a decoupled stratocumulus~~ (~~DSC~~1a) ~~layer not over cumulus. The IWP~~ and ~~LWP are calculated collectively over these types.~~ (~~2a~~1c) ~~and (2c)~~ represent annual-mean; (~~2b~~1b) and (~~2d~~1d) represent DJF mean. The colour codes are as follows: red = anomaly of ~~exp1~~ *cap* with respect to control, black = anomaly of ~~exp2~~ *c_tnuc=-40* with respect to control, yellow = anomaly of ~~exp3~~ *c_tnuc=-20* with respect to control. Values are calculated from 12 hourly instantaneous model output over 20 years. The SO region identified in this study is highlighted in gray.

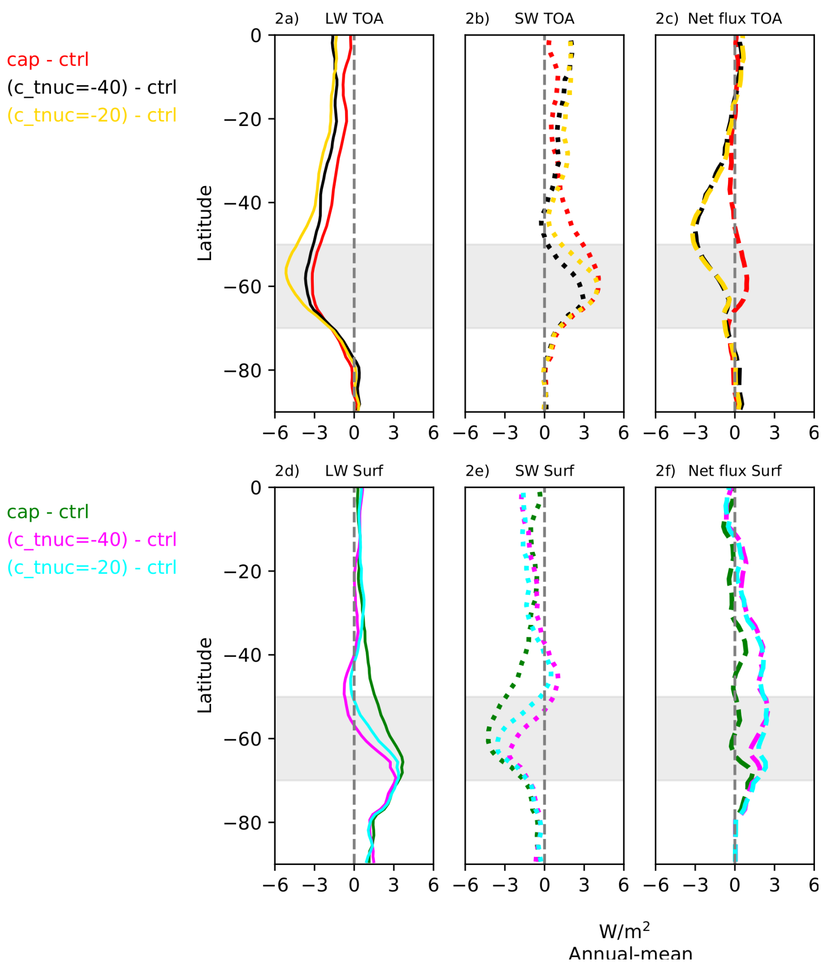


Figure 2. Distribution of zonally averaged annual-mean radiative flux anomalies in various experiments ~~and observational data~~ with respect to the model control run for the SH. ~~3a~~(2a) to ~~3e~~(2c) represent the TOA (upward) radiative flux anomalies and (2d) to (2f) represent the surface (downward) flux anomalies. The solid lines in (2a) = LW at TOA, dotted lines in (2b) = SW at TOA and dashed lines in (2c) = net flux at TOA (i.e. LW + SW ~~radiative~~ at TOA). Color codes for TOA fluxes are: red = *cap* - control ; black = (~~leaving~~ *c_tnuc=-40*) - control and yellow = (*c_tnuc=-20*) - control. Similarly, the ~~TOA as well as the~~ solid lines in (2d) = LW at surface, dotted lines in (2e) = SW at surface and dashed lines in (2f) = net ~~downward~~ radiative heat flux at ~~the~~ surf (i.e. incoming LW + SW at surface - (sensible heat + latent heat). Color codes for ~~exp1~~ surface fluxes are: green = *cap* - control ~~, exp2~~ ; magenta = (*c_tnuc=-40*) - control and ~~exp3~~ cyan = (*c_tnuc=-20*) - control~~respectively~~. ~~3d~~Annual-mean values for model are calculated from daily-mean output over 20 years. The SO region identified in this study is highlighted in gray.

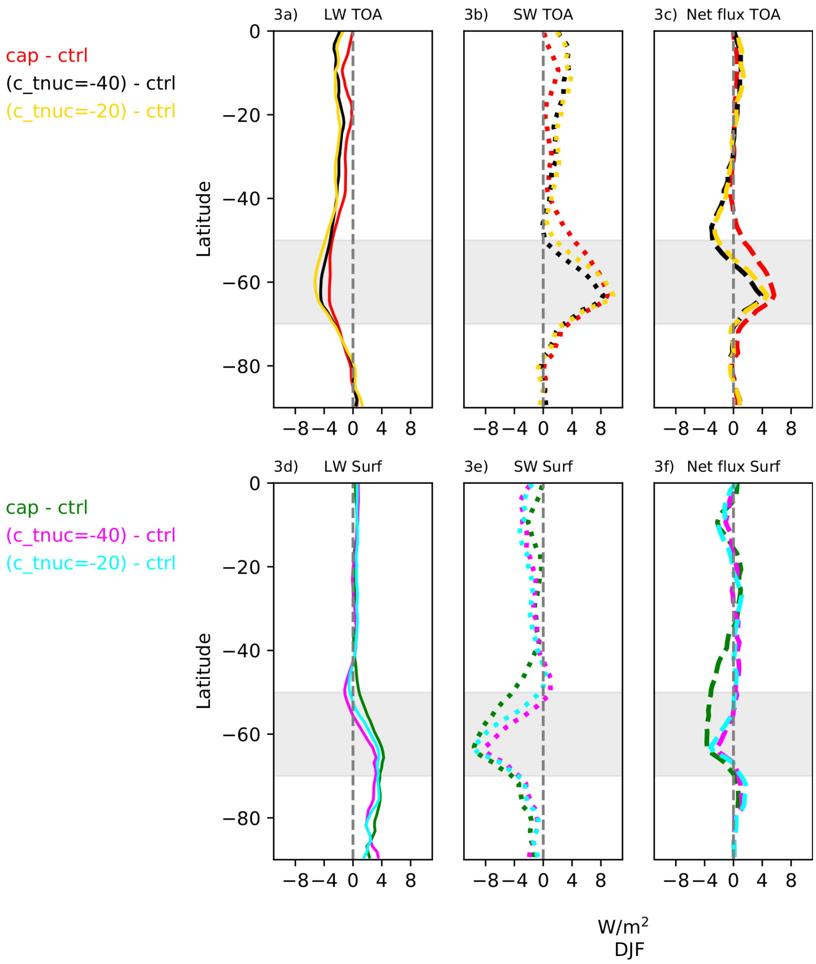


Figure 3. Similar to Fig 2. but for DJF season

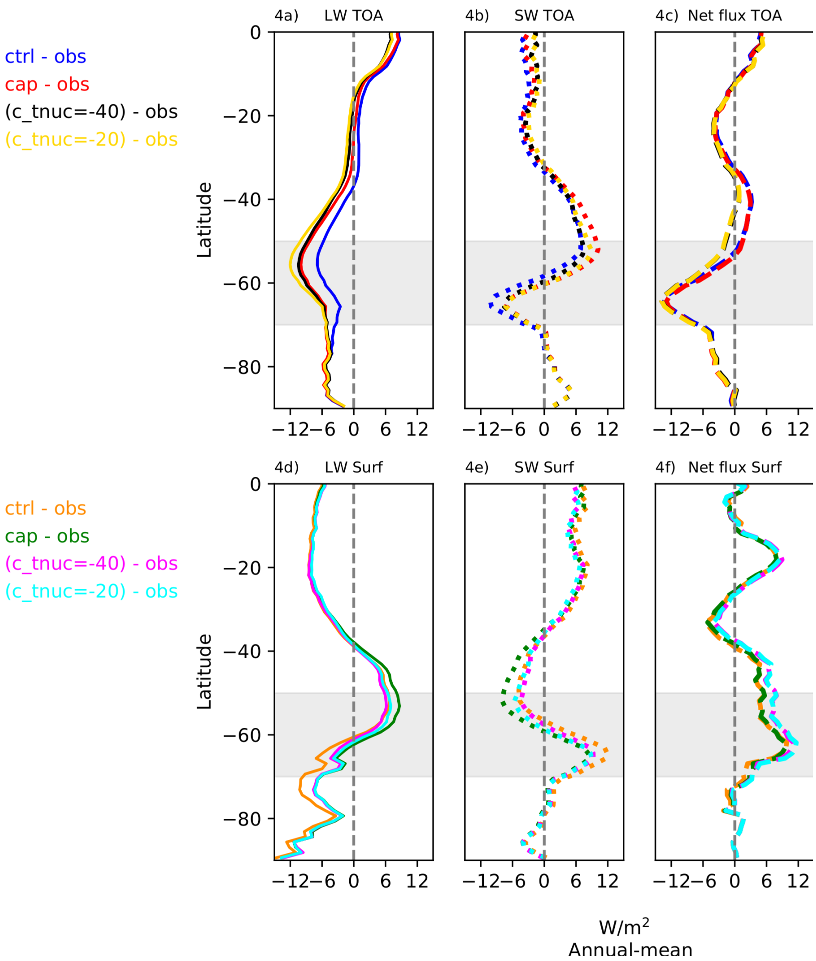


Figure 4. Distribution of zonally averaged annual-mean radiative flux anomalies in various model experiments with respect to observations for the SH. (4a) ~~similar~~ to (~~3a~~4c) ~~but for observational data - control~~represent the TOA radiative flux anomalies and (4d) to (4f) represent the surface flux anomalies. The ~~colour codes are as follows: red~~ solid lines in (4a) = LW at TOA, ~~black~~ dotted lines in (4b) = SW at TOA ~~,~~ ~~mustard~~ and dashed lines in (4c) = ~~LW~~ net flux at TOA (i.e. LW + SW at TOA). Color codes for TOA fluxes are: blue = control - obs; red = *cap* - obs; black = (*c_tnuc=-40*) - obs and yellow = (*c_tnuc=-20*) - obs. Similarly, ~~magenta~~ the solid lines in (4d) = LW at surface, ~~gray~~ dotted lines in (4e) = SW at surface ~~, blue~~ and dashed lines in (4f) = ~~LW surface + SW surface, cyan =~~ net radiative heat flux at surf (i.e. incoming LW ~~surface~~ + SW at surface ~~)~~ - (sensible heat + latent heat). ~~Solid lines represent radiative flux anomalies from model~~ Color codes for surface fluxes are: orange = control - obs; green = *cap* - obs; magenta = (*c_tnuc=-40*) - obs and ~~dashed lines represent anomaly of observational data w~~cyan = (*c_tnuc=-20*) - obs. ~~r.t control run.~~ Annual-mean values for model are calculated from ~~12 hourly~~ daily-mean output over 20 years. ~~Observational~~ The net surface flux observational data ~~consist~~ is a combination of ~~monthly mean values covering the period 2000-2018~~both TOA fluxes from satellite and ERA-Interim reanalysis energy divergences (details in Section 2.2). The SO region identified in this study is highlighted in gray.

~~Similar to Figure 3 but for DJF season.~~

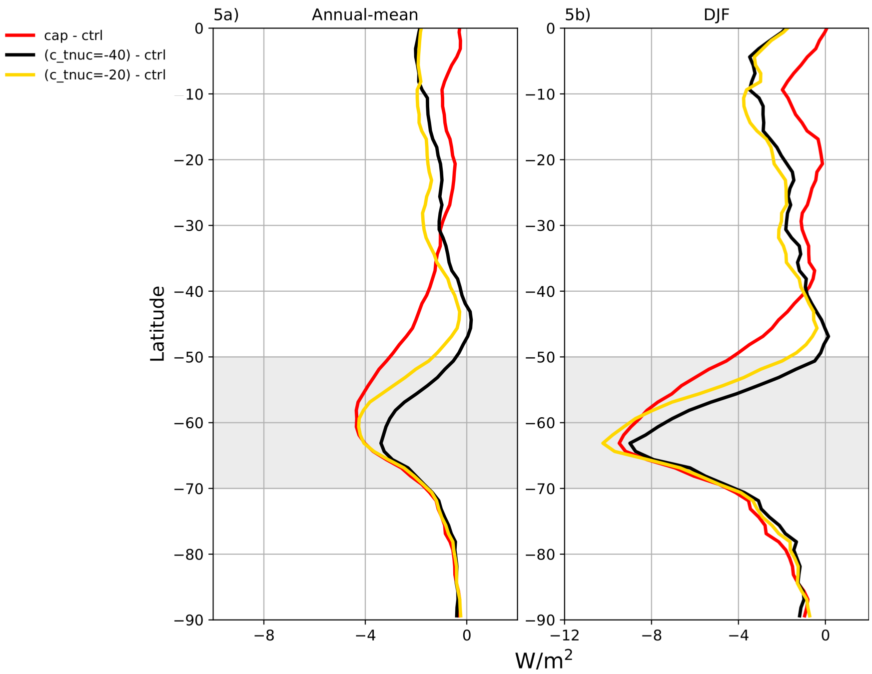


Figure 5. Distribution of zonally averaged SW CRE anomalies over SH in various experiments ~~w.r.t~~ with respect to the model control run for (5a) annual-mean and (5b) DJF mean. The colour codes are as follows: red = ~~anomaly of exp1 with respect to~~ *cap* - control, black = ~~anomaly of exp2 with respect to~~ (*c_tnuc=-40*) - control ~~,~~ and yellow = ~~anomaly of exp3 with respect to~~ (*c_tnuc=-20*) - control. Values are calculated from ~~12 hourly~~ daily-mean output over 20 years. The SO region identified in this study is highlighted in gray.

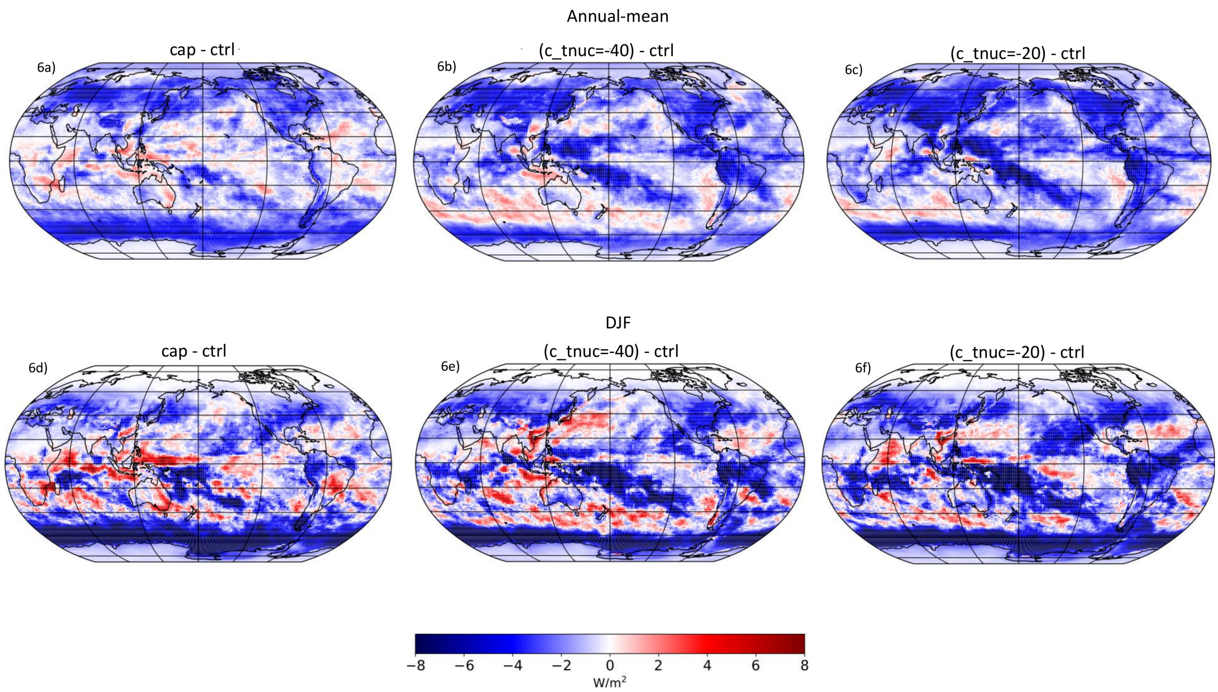


Figure 6. Spatial ~~distribution~~ distributions of annual-mean ~~SW CRE anomaly between model and observational data.~~ (6a) to (6c) and DJF mean (6d) to (6f) SW CRE anomaly at TOA in ~~an earlier model version~~different experiments with respect to the control run. (6a) and (6d) = *cap* - control, ~~GA6 (Walters et al., 2017)~~ (6b) ~~Similar to~~ and (~~6a~~6e) ~~but for the model version GA7 (Walters et al., 2019).~~ = (*c_tnuc=-40*) - control, (6c) ~~Similar to~~ and (~~6a~~6f) ~~but for the~~ = (*c_tnuc=-20*) - control~~model used in this study~~. ~~Annual-mean for each model version is~~ Values calculated from ~~one year of daily mean data~~daily-mean output over 20 years.~~Observational data is similar to the one used in Figure 3.~~

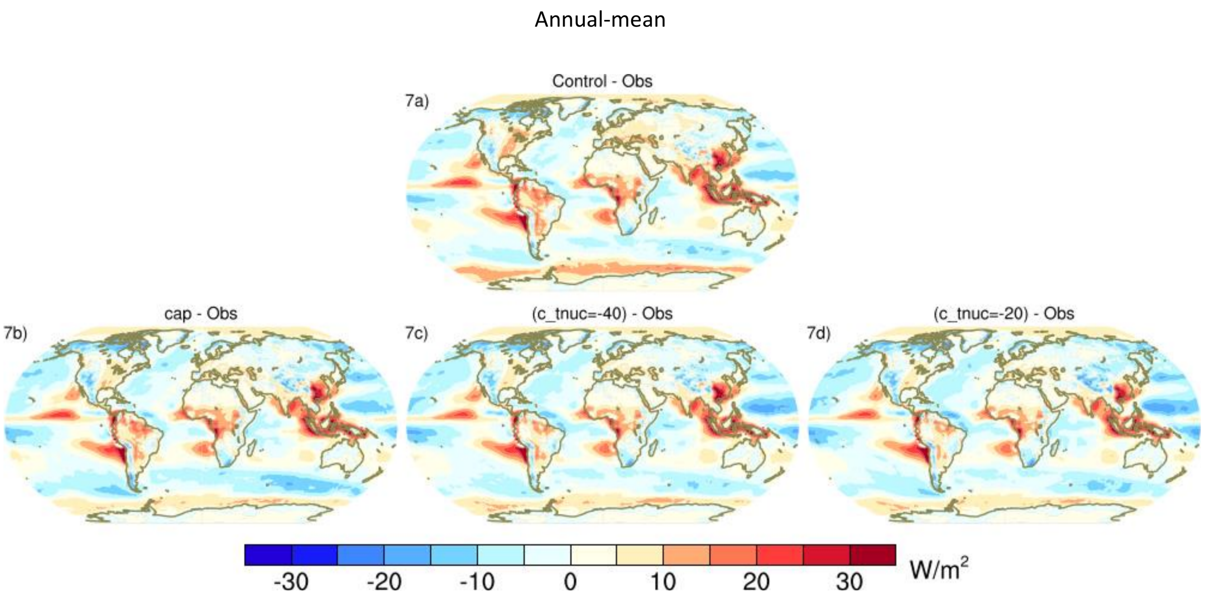


Figure 7. Spatial ~~distribution~~ distributions of ~~annual-mean~~ annual mean SW CRE anomaly at TOA in different ~~sensitivity experiments w.r.t~~ model simulations with respect to the ~~control run~~CERES TOA data. (7a) ~~exp1 –~~ = control ~~,~~ - Obs ; (7b) ~~exp2~~ = *cap* - ~~control~~Obs, (7c) ~~exp3~~ = (*c_tnuc=-40*) - ~~control~~Obs; (7d) = (*c_tnuc=-20*) - Obs. ~~Annual-mean values are~~ Model data calculated from ~~12 hourly~~ daily-mean output over 20 years. Observational (CERES EBAF TOA) data consist of monthly mean values covering the period 2000-2018