

Response to Reviewer 2

We thank Reviewer 2, Alex, for your positive comments and constructive feedback on our manuscript. We have expanded on our methods to make more clear how and why we have chose the methods we did and we have tried to include more discussion of SCLW throughout. We have now included one of the Figures requested in the main text, while the others are in supplementary material. We have addressed each comment below.

Major comments

In the current manuscript the normalisation of the cloud top pressure - cloud optical thickness joint histograms is ambiguous. For the majority of prior papers using these histograms, they are normalised by the cloud fraction value so that the sum of the cells of the histograms add to the cloud fraction value. If I had to guess based on figure 2, each of the histograms in this study are normalised to a value of 1 (I could be wrong about this). If this is the case it will have some implications on the interpretation of the results with respect to prior studies. This alternative normalisation could be justified by arguing the paper's focus is on phase and vertical structure which may be better captured with this approach, however currently I cannot find any discussion of this in the paper and it should definitely be discussed. While not expected in this paper, it could be interesting to compare results of these different normalisations.

Thank you for raising this issue. Yes you are correct, we have normalised our histograms to one, and not to the cloud fraction. We have found that this has yielded better results for our clustering methods, as it reduces the effect of biases in cloud fraction on the clustering. ACCESS-AM2 has significant cloud fraction biases, which is shown by the ice and water phase cloud fractions discussed within, but is also true for the total cloud fraction which has not been discussed in this work. If we normalise the histograms to the cloud fraction, we get sensible cloud regimes from the MODIS product, as expected, but when this is applied to the ACCESS-AM2 histograms, the majority of points are assigned to a singular low cloud fraction cluster (eg. less than 30% coverage), with no real height or optical property definition. This considerably effects our analysis. By normalising to one, the clustering focuses more on the clouds vertical profile/optical depths, without the biases introduced by the ACCESS-AM2s poor simulation of cloud fraction. This is not to say that the cloud fraction bias is unimportant, but we discuss this bias in detail in other parts of the manuscript. We have attached the figures for both methods here for your interest (Figures 1 and 2) and we have also made sure to clarify our methods in the text.

Line 197: 'We have normalised the CTP/ τ histograms to one (as opposed to the cloud fraction) to limit the impact of cloud fraction biases within the ACCESS-AM2 model on the clustering results. Whilst this impacts our ability to compare to other studies, it allows the clustering to target cloud vertical extent and thickness regardless of the total fraction and how well it is captured by the ACCESS-AM2 model.'

I am surprised by the lack of discussion of supercooled liquid water throughout the manuscript. There are several places, particularly in your results, where I think some discussion is warranted. Many of your results show too much ice fraction and not enough liquid in key cloud types which is indicative to me of issues with the model representation of supercooled liquid water. Some good places to add this would be the paragraph starting on line 273, the discussion of figure 7-9 and the conclusions.

Thank-you for pointing this out. We have now including discussion of SCLW throughout the manuscript as appropriate, including below:

Line 286: 'This finding agrees well with the literature in that not enough liquid water exists below zero degrees Celsius, instead being simulated as ice (Bodas-Salcedo et al. 2016)'

Line 294: 'The role of cloud phase, and in particular, that of supercooled liquid water, appears to have significant latitudinal dependence, likely influenced by a range of factors, including temperatures and ice nucleating particle (INP) availability.'

There are some figures that are passingly discussed in the text but not currently in the paper which would make great additions to an appendix. In particular, I am thinking about the phase property versions of Figure 5 and the individual sub-region versions of Figure 6. I know I would be interested in seeing

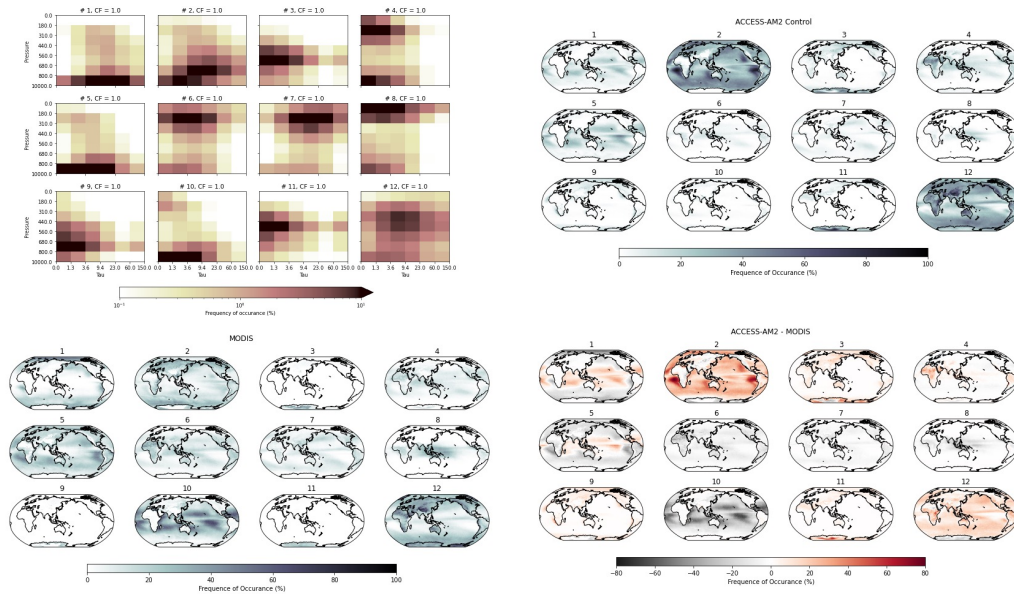


Figure 1: Clustering when normalised to one, as done in this study

those figures and the most appropriate place via ACP guidelines appears to be in an appendix.

We have added the cloud phase versions of Figure 5 as supplementary material. We have now replaced Figure 6 with the three subplots of the sub-regions.

Minor comments

Line 7: Sentence starting on this line should be simplified due to its complex clausal structure.

We have altered this sentence as follows:

Line 9: ‘We find that when the ACCESS model correctly simulates the cloud type, cloud property and radiation biases of equivalent, or in some cases greater, magnitude remain when compared to when cloud types are incorrectly simulated.’

Line 20: Consider changing “simulation by models of cloud properties” to “simulation of cloud properties within models”

Sentence changed as suggested.

Line 46: Consider changing “compensate the” to “compensate for the”

Sentence changed as suggested.

Line 84: I think something has gone wrong with the citation formatting here

Yes, citet instead of citep. Fixed now.

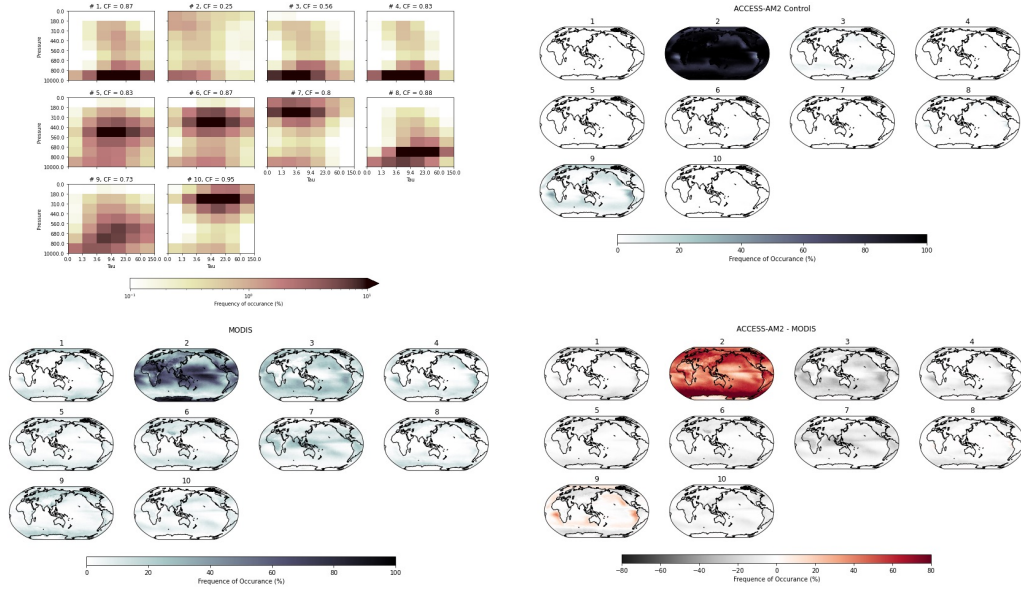


Figure 2: Clustering when normalised to the cloud fraction

Line 153: *Can you please be more specific about the identification of clear sky cases and their removal from the dataset*

Instances of clear sky were determined by summing the histograms. Any histogram that added up to zero was removed from the data set with which clustering was applied to.

Line 162: ‘We have done this by finding the instances where the CTP- τ histograms summed to zero.’

Line 190: *I think you have cited the wrong paper by mistake here. From what I can see Pendregosa 2011 does not have that information.*

We were referring to the SciKit Learn API, which Pedregosa 2011 is the reference for. We have made this more clear.

Line 205 ‘The SciKit Learn application programming interface provides a detailed explanation of each metric in addition to their advantages and disadvantages.’

Section 3 could possibly do with some references to past paper which have identified similar seasonal (Bodas-Salcedo et al. 2012) or spatial (eg. Kuma et al. 2020) biases

We have included references to these papers in this section as suggested.

Line 234 ‘The summer (DJF), shown in Figure ??c1, continues to have the largest polar bias, while the winter (JJA) season has the smallest bias overall, in agreement with previous work (Bodas-Salcedo et al. 2012, Kuma et al. 2020).’

Line 244 ‘Kuma et al. (2020) also noted a strong latitudinal dependence of radiative biases in a similar version of the UM and a reanalysis product.’

Line 225: Consider changing “less zonal” to “less zonally coherent”

Sentence changed as suggested.

Figure 1 appears to have an issue where some rows are more magnified than others leading to some straight edges

We have amended the Figure to resolve this issue.

Line 261: I think “indicating that this is a complex system to understand” should be changed to something that stresses the behaviour in the system is complicated in place of how understandable it is.

I have removed ‘to understand’ to this effect.

Line 282: Simplify the wording of “using 12 clusters for five years of daily-mean joint histograms”

Sentence simplified to:

Line 304: ‘The k -means clustering technique, spanning five years of daily-mean joint histograms over the entire globe, resulted in the 12 cluster centres shown in Figure 2.’

Line 288: Consider deleting “while this is important to note,”

Deleted.

Figure 3 and 4: The last sentence in the caption is a little unclear and awkwardly worded. Consider simplifying.

Simplified to:

Figure 3 & 4 captions: ‘The numbers in each title represent the mean frequency of occurrence for each cloud regime (in time and space) over SO region’

Line 327: Consider deleting “region of interest”

Deleted

Line 328: Consider rewording “are spatially consistent in sign and for some, magnitude” as it is a little confusing.

We have removed ‘and for some, magnitude’ to this effect

Line 333: The sentence stating on this line may need some rewording as it could imply you do not look at subregions instead of the intended meaning that non-SO data is excluded.

We have amended this sentence:

Line 355: ‘Note that from this point on we only consider the broad SO region, and the three sub-regions defined within.’

Line 371: I found the wording of the first three sentences of this paragraph quite hard to follow. I would suggest rewriting them with an emphasis on clarity.

We have significantly revised this section to outline more clearly our methods. We have also added another figure to help aid the readers understanding (Figure 6).

Line 403: ‘Each panel of Figure 7 shows for each MODIS cloud type (y-axis), the percent of time that each cloud type is assigned by ACCESS-AM2 (x-axis). The total number of instances that that cloud type is observed by MODIS for each region is shown on the right. If ACCESS-AM2 simulated every cloud type the same as what the MODIS product did, we would expect a diagonal line through Figure 7 of 100%, with zeros elsewhere. ’

Section 5.2.1 even though it is incredibly rare, a sentence discussing the extreme phase based biases shown in the TC class could be a valuable addition here.

We have added a sentence discussing the TC biases. We do not feel that we can draw much for this results, as this type of cloud is occurring approximately 85 times in the the whole data series (see Figure 6, 8547 / 1%).

Line 474: ‘The thin cirrus clouds are shown to have large biases in the spring (SON) when correctly simulated for all fields. However, we note that these cloud types occur infrequently (see Figure ??a, total number for thin cirrus clouds) and are only correctly simulated 1% of the time, and hence, we do draw any conclusions from this result. ’

Line 401: The transition to a new sentence discussing mid-level clouds feels off, because I assume the previous sentences were already discussing them. I think this could probably just be resolve with some more clear wording

We have significantly revised this paragraph (and section) to make it clearer.

Line 428: ‘For the mid-level and marine stratiform clouds, the $SWCRE_{TOA}$ biases are larger when the cloud types are assigned incorrectly (outlined bars) than when they have been correctly simulated by ACCESS-AM2 (coloured bars). However, when these cloud types are correctly assigned (which happens 63% and 12% of the time respectively), the $SWCRE_{TOA}$ bias are for most cases non-negligible in most seasons. For the mid-level clouds, the $SWCRE_{TOA}$ biases are smaller in magnitude when the clusters are correctly identified by the model. Interestingly, this is not the case for the CFL and LWPs, which both have larger biases when the clusters agree, suggesting that the radiative effects associated with too few liquid water clouds is partially compensated by them being too optically thick. This indicates that the lower $SWCRE_{TOA}$ bias when the mid-level clouds are correctly simulated may be occurring for the wrong reasons. For the marine stratiform clouds, the CFL is strongly underestimated when it is incorrectly simulated, which is expected to produce negative $SWCRE_{TOA}$ biases. The CFI is comparatively well simulated. Interestingly, the LWP and IWPs seem to be relatively well captured for marine stratiform clouds. This suggests that the $SWCRE_{TOA}$ bias may be predominantly driven by an underestimated CFL, while the amount of water in them is somewhat correct.’

For figures 7-9 I think the exact definition of the total column is unclear. I can't determine if it shows the overall biases associated with accurately simulated clouds or with all clouds. If it is showing for both “incorrectly” and “correctly” represented cloud types combined, it could be interesting if there was a way to decompose this information and show each independently. Regardless of if this is possible or not, some text needs to be added clarifying what this column represents.

We have removed the total column here to avoid confusion.

Line 446: The sentence starting on this line is confusing due to its clausal structure. Can you simplify the sentence or split it into two.

We have rephrased as follows:

Line 482: ‘The mid-level and stratocumulus clouds at the two most accurately simulated cloud types (68% and 66% of the time). The cloud radiative biases in these cases are relatively low, implying that the model may be doing a good job.’

Line 449: Consider deleting the “For” at the start of the sentence.

Removed.

Line 454: Please simplify “Considering now what may be contributing to”

We have rephrased as follows:

Line 491: ‘We can see that the majority of the positive bias in the sub-polar region is driven by shallow cumulus clouds, that are incorrectly simulated.’

Line 531: I think the sentence starting on this line is a little confusing and would benefit from being rewritten.

We have simplified this sentence as follows:

Line 571: ‘Marine-stratiform, stratocumulus and mid-level clouds contribute most to the polar region’s negative SWCRE_{TOA} bias.’

Line 533: Consider deleting “biases, again whether the cloud regime is correctly simulated or assigned as something else,”

We have revised as follows:

Line 571: ‘Each of these cloud types are associated with large biases in cloud properties, including too few liquid clouds, too little LWP and too much IWP. This is the case both for when these cloud types are correctly and incorrectly assigned.’