We would like to thank the referees for their thoughtful and useful comments on our paper. We have responded to the individual comments below, and modified the manuscript in several places to accommodate the improvements and clarifications requested by the referees.

In the text below, reviewer comments are in black, and our responses are in red.

In response to the comments on the assumption regarding the treatment of OC and BC, we have added detailed text and references explaining the use of this assumption, and the implications. We have also added a more detailed discussion of the scaling factor used for the emissions, supported by references to the literature. As both referees suggested, the section of the paper on the monsoon has been greatly shortened, as the lack of definitive conclusions here did not require a detailed description.

All responses are detailed below, and also in the accompanying revised manuscript.

Anonymous Referee #1

General comments:
I find the paper by Thornhill et al. interesting, clear and well-written, and it should fit into the scope of ACP. Biomass burning aerosol emissions are high in South America, and information on how these emissions may impact the regional climate is of value. However, I have some comments and questions that need to be addressed before I could recommend the paper for publication. My main comments concern methodological choices and model evaluation. Please see specific comments below.

We thank the reviewer for their comments. We have incorporated some responses to reviewer 2 into the responses below here for reviewer 1 since many of the comments were similar.

Specific comments:
Page 1, lines 15-18: It would be good to include uncertainties to the numbers given.
Uncertainties (standard error) have been added to the numbers.

Page 2, line 25: Feingold et al. (2005) is also a relevant reference here. Feingold, G., Jiang, H. L., and Harrington, J. Y.: On smoke suppression of clouds in Amazonia, Geophys. Res. Lett., 32, 2, L02804, 10.1029/2004gl021369, 2005.
Thank you, interesting results in this reference have been referenced in the manuscript.

Page 5, line 9: What levels of CO2 and other greenhouse gases were used? Representative of the 2000s?
Levels of greenhouse gases and other trace gases were fixed at levels representative of the year 2000 identical to Shaffrey et al. (2009). Ozone is a seasonally varying two-dimensional latitude-height field from Randel and Wu (1999) – this has been added to the manuscript.

Page 5, line 16: Isn't it a rather strong assumption to have BC and OC lumped into one species, given their very different properties (e.g., hygroscopic growth, radiative properties)?

Firstly, we would like to clarify that in CLASSIC, in addition to a biomass burning tracer, the species fossil-fuel BC and fossil-fuel OC are represented separately, by different tracers (in addition to the other aerosol species described in the paper) as stated on p5 lines 10-12.

In CLASSIC, the BBA aerosol tracer has two components: fresh and aged BBA, which were originally designed to correspond to different BC:OC ratios, as described in the paper. This assumption is justified by the fact that BC and OC are internally mixed in biomass burning aerosol particles. In addition, both remote sensing and in-situ aircraft observations characterize the ambient biomass burning aerosols, rather than their BC and OC components. Therefore although climate models which separate BC and OC may appear more sophisticated, we lack the observational constraint to support and validate their complexity, particularly in BBA source regions. Representing BBA as a separate aerosol tracer in fact allows its microphysical and optical properties to be specified using recent BBA observations newly available at the time of model development. Even more recent observational campaigns (such as SAMBBA) still for the most part provide information on the bulk BBA aerosol and so this formulation within the model allows adjustment and evaluation of the microphsyics using the more recent SAMBBA field campaign results.

Section 2.1 has been re-written to provide more explanation of this approach.

We agree that our model does not represent spatial changes in vegetation type which may contribute to different aerosol regional composition and therefore different spatial optical properties. Most observational campaigns suggest that aerosol ages very rapidly following emission which would be expected to remove some of the variability. We are aware of a few SAMBBA measurements that have been made showing some differences in single scattering albedo between east and west Amazon area, but these measurements are few and far between. We did in fact run some additional simulations with SSA altered informed by these measurements, but the impacts were very small.

Text has been added to section 2.2 to better recognise this possible influence.

Page 5, lines 29-32: How are the high level emissions distributed among the different model levels 3 to 20? Is the vertical information given by GFED, or is it done online in the model, e.g., by a plume rise routine? I would expect your results to be very dependent on how the emissions are distributed vertically, e.g., to what fraction of emissions occur within or above the boundary layer.

High level emissions are distributed equally in mass between model levels 3-20. Vertical information is not available from GFED, and is performed internally in the model. No plume rise routine is included.

Although we agree that a more detailed representation of emissions in the vertical should give better results, recent efforts to examine whether varying the vertical distribution of emissions has a strong impact have found the reverse. E.g. Veira et al. (2015, ACP) examined this and found "simple plume height parametrizations provide sufficient representations of emission heights for global climate modeling." The modelled vertical BBA profile is affected by emissions, transport, and removal processes, and despite the simple vertical emission distribution, CLASSIC is able to reasonably capture the shape of the vertical profile as well as the column AOD when compared to observations (Johnson et al., 2016). Section 2.2 has been adjusted to include this extra information.

Page 6, line 1: Have the monthly, daily or 3-hourly GFED data been used?

Monthly GFED data have been used, now stated in Section 2.2.

Page 6, lines 4-7: Scaling the emissions by a factor of 2 is a rather extreme measure that needs to be justified. Is this factor solely based on the previous literature cited, or have you done any experiments in this study to reach a conclusion that a factor of 2 gives more realistic results?

We agree, this is an important point, which deserves further explanation.

Applying a global emission scaling factor is not a new method. Reddington et al. (2016) (their Table 2) show that multiple modelling studies have used scaling factors of up to values of 6 in the past; attempting good agreement between modelled and observed BBA AODs and particulate matter concentrations is a continuing problem. Johnson et al. (2016) also discuss the issue, noting that many studies have had to apply values >1 in order to gain agreement between modelled and observed AODs and/or particulate matter measurements for BBA regions, such as Kaiser et al., 2012; Marlier et al., 2013; Petrenko et al., 2012; Tosca et al., 2013; Archer-Nicholls et al., 2016; Kolusu et al., 2015; Reddington et al., 2016.

Specific experiments have not been performed in this study to choose a factor of 2, but have been done as part of the wider SAMBBA project (Johnson et al., 2016; Reddington et al. 2016), which have also included the same climate model and aerosol scheme (Johnson et al., 2016). Johnson et al. (2016) use a scaling factor of 1.6 for CLASSIC, and here we increase this to 2, which is required to be higher as a consequence of decreasing the f(RH) curve to be consistent with the SAMBBA aircraft observations.

Reddington et al. (2016) find that of many model properties, hygroscopic growth factors were most important in determining the required emission scaling factor. Thus we might expect to need to increase modelled hygroscopic growth in order to match models and observations of BBA; yet we find the reverse: the SAMBBA observations suggest that CLASSIC is already too hygroscopic (Johnson et al., 2016 and this work). Therefore we conclude that at this stage, we cannot solve the scaling factor problem within the scope of this paper, and urge further work in this area - both by future field work and modelling studies aiming to reduce these uncertainties.

It should also be noted that there are significant differences between different emission inventories, as well as between subsequent versions of the same emission dataset (van der Werf et al., 2010; Reddington et al., 2016), so they should by no means be seen as perfect or set in stone.

Section 2.2 has been expanded to include all these points.
We have also added some points about the scaling factor in the conclusion as we feel it is an important issue.

Page 6, lines 31-33: Any idea why the hygroscopic scattering growth is so different between southern African and Amazonian BBA? Is it likely due to some regional-specific properties (e.g., climatological differences), or is it more related to how the measurements were conducted?

It is difficult to reconcile the different f(RH) curves between Magi and Hobbs (2003) for southern Africa and Kotchenruther & Hobbs (1998) for southern America. Both studies report airborne observations using a humidified nephelometer. MH2003 do not comment on why their 'regional air' is so hygroscopic, or contrast their observations to KH98. Johnson et al. (2016) hypothesize that the 'regional air' classived in MH2003 may have contained a substantial amount of hygroscopic industrial sulfate aerosol, which could have behaved differently. Davison et al. (2004) show some evidence that if combustion of peat swamps is involved, gas to particle conversion can produce high sulfate contributions to the BBA. We anticipate new state of the art observations from the recent CLARIFY project observations within the Southern African BBA plume to expand on this issue shortly.
These points have been added to the manuscript.

Page 6, line 33: Are these values for fresh and aged BBA, respectively?
No, these values refer to the range presented in KH98, which are for regional haze from 4 different regions of Amazonia. This is now clarified in the manuscript.

Page 7, line 2: Looks like you have taken the lower value (1.05 for 80% RH) from Kotchenruther and Hobbs (1998) when drawing the green dashed line in Fig. 3. What is the reason for that? Also, did Kotchenruther and Hobbs (1998) find any difference in the optical properties between fresh and aged BBA, or did they conclude that these were similar as in SAMBBA?
This is correct, we have taken the lower value curve (1.05 at 80% RH) - this represents the KH98 Porto Velho data, which was the same location as the SAMBBA aircraft observations. There may not be a strong reason for selecting this lower curve on a global scale in a climate model, and therefore we acknowledge that our AODs should actually be viewed as a lower limit - they could be higher in the model if we had adopted, say, f(RH) curves with values as high as 1.29 at 80% RH, which could still be realistic. This is now added to the manuscript.

Page 9, lines 4-7: Doesn't this show that BB BC and OC should be treated separately?

Please see response to BC/OC BBA representation above.

Page 10, line 13-14: "see figures" is very unspecific. I suggest referring to Fig. 5 (i.e., "see Fig. 5"). Similarly for Table 1 caption ("which is outlined in each figure").
This has been corrected by referring to the figure explicitly.

Figure 5 caption: Suggest changing to "used to calculate the mean values in Table 1".
Figure 5 caption: "Stippling represents 95% confidence limit". I presume this is based on the interannual variability, i.e., a Student's t-test on the yearly time series? This comment also applies to the other map figures.
The caption has been changed as suggested.
The significance was calculated using the Student T-test over the time series to distinguish between changes due to the emissions differences, and changes due to inter-annual variability. Text has been added to the manuscript to describe this in more detail.

Table 1: It would be good to include some uncertainties here, to be able to assess whether or not the changes are significant. E.g., I expect the AOD change to be significant, but I am not convinced that this is the case for the change in cloud fraction. Changes that are significant (e.g., based on a Student's t-test on the yearly time series) could be indicated in bold.

Uncertainties have been added in to the table.

Table 1: I would show the % change either as (H-L)/L or (L-H)/H.

There are several ways to define and express these changes, but we have decided to retain the percentages as expressed, with the clear description of how they were calculated.

Page 12, line 4: Table 1 shows 70.6% reduction.

Figures in text and table have been corrected.

Figure 6: I find the colour scale a bit confusing because I normally associate brown colour with drying. I suggest using blue colour for high cloud fraction and brown for low cloud fraction.

Colour schemes can be very much a matter of personal taste and style. We prefer to keep consistency across the entire paper, where brown/red indicates an increase in a parameter and blue indicates a decrease, for all variables except precipitation, where bluer colours indicate more precipitation. We prefer to leave Figure 6 as it is, clearly labelled with a colour bar, under the concept that browner colours show an increase.

Figures 10-11: Stippling is not mentioned in the captions.

The caption has been corrected to include description of stippling.

Page 17, lines 1-2: Any reason why it is negative?

The difference here is very small, so the change here is not significant.

Page 19, lines 3-4: Do you mean "we can see the semi-direct effect through cloud burn-off, but the ..."?

Text corrected.

Page 20, line 2: As mentioned earlier, it would be good to include uncertainties to the mean numbers. E.g., 0.14+/-X.XX degrees C.

Uncertainties have been added in the text as suggested.

Page 20, lines 3-4: Should mention that the increase is not significant.
Page 21, line 3: The precipitation increase is also not significant.

For both these have added text to indicate significance or lack thereof.

Page 21, line 4: Table 1 shows 15.2%.

Discrepancies between the table and text have been corrected.

Figure 16: The caption has a lot of unnecessary repetition. Please rewrite (e.g.,

"September mean wind circulation at 850 mb for (a) high emissions case, (b) low emissions case, and (c) the difference between high and low emission cases...."). Also, the common unit for atmospheric pressure is Pascal and not millibar. I would replace "mb" with "hPa".

The caption has been rewritten to remove the repetition.
The units have been changed to hPa.

Page 21, line 16: Please correct Figure numbers.
Figure numbers have been corrected (refers to Supplement figures).

Page 21, lines 16-17: Good to see that the model compares relatively well with ERAInterim for surface pressure and wind. How does the model compare for other important variables, such as cloud cover and precipitation, in the South America region?
Has this been published before, or could you extract more variables from ERA-Interim to expand the comparison?
We have extended the comparison to clouds cover and precipitation. However we include these figures in the supplement in order not to lengthen the main paper. They show the model broadly reproduces the general patterns of cloud cover and precipitation for September.

Figure 17: The figure quality is not good. The titles and axis labels are small and not readable. Please improve. The same comment applies to Figs. 18-19.
Figures have been changed or removed as part of the re-write of the monsoon section, and the quality of the new figures has been improved.

Page 25, line 5: Insert "(Fig. 19)" after "S. America".
Corrected.

Page 27, lines 18-22: In general I find the discussion in Section 4 a bit too detailed and inconclusive. Given that no conclusion on the BB impacts on the monsoon can be reached, due to missing daily output in the experiments, I think the paper would benefit from a substantial shortening of Section 4. For instance, you could keep Fig. 19 and part of the Fig. 19 discussion, and move Figs. 17-18 and most of the associated discussion to the Supplementary Material.
We acknowledge that there is too much weight given to this section and thank the reviewer for their suggestion. We have moved the figures showing similarities to previous work to the supplement, and include only a figure showing the effect of emissions in October and November in the main paper, alongside a much shortened discussion.

Page 31-34: The reference list needs a lot of cleaning up to comply with the format used in the ACP journal.
We were surprised to read this comment as we used the ACP template and reference format. We cannot see any inconsistencies or errors, so refer this point to the editorial team. We will be happy to correct any specific errors.

Technical corrections:

Page 9, line 7: Fig 4 -> Fig. 4
Figure 7: Please remove or change "Cloud Amt" -> "Cloud Amount" in legend.
Figure 7 caption: "mass mixing ratio" -> "mass mixing ratio (MMR)"
Figure 8 caption: "Deep" -> "deep"
Page 14, line 26: "Fig.9" -> "Fig. 9"
Page 15, line 1: "reduces" -> "reduce"?
Page 15, line 13: "CS" -> "clear sky"
Page 18, line 7: ", illustrates" -> "illustrate"
Page 20, line 4: "Fig.15(a))" -> "Fig. 15(a)"
Page 22, line 3: "Fig. 15(c)" -> "Fig. 16(c)"
Page 22, line 11: "patters" -> "patterns"
Page 22, line 14: "suggestuing" -> "suggesting"
Page 23, line 28: "(18(a-d-g)" -> "(Fig. 18(a-d-g))"
Page 25, line 6 and 7: "dryer" -> "drier"
Page 25, line 31: "andout" -> "and out"
Page 27, line 22: "a results" -> "a result"

These corrections have been done, Fig. 7 legend fixed.

Anonymous Referee #2

I have reviewed the manuscript titled "The Effect of South American Biomass Burning Aerosol Emissions on the Regional Climate." The manuscript uses observations from the SAMBBA campaign to constrain the aerosol scheme in the HadGEM3 model. Multiyear experiments are run using representative low and high biomass burning years and the resulting impact to the regional climate is assessed.
While the study fits within the scope of ACP, after careful consideration I cannot support publication as written. I believe that significant revisions are required prior to consideration in ACP. The manuscript is well written to some extent, but does contain several typos and one section needs to be made more concise. More importantly, I believe there are some flaws in the assumptions that must be addressed by the authors, and the novelty of the study in my opinion (running several years of experiments using a low and high case of biomass burning) is not sufficiently explored. Below are my major comments, followed by more specific comments.

We thank the reviewer for their comments. Since many of the comments overlap with those of reviewer 1, we refer the reviewer to the responses to reviewer 1 in many cases.

Major Comment 1: The manuscript does not include any model comparisons with observations.
First, I would expect that some of the key assumptions made in the study would be verified through comparisons to observations, such as the assumption that the GFEDv3.1 emissions data should be scaled by a factor of 2. Is this because of issues with the GFEVv3.1 database or because the hygroscopic growth in the model was lowered? Second, I would expect that the model results be compared with in situ and remotely-sensed observations to ensure it is appropriately representing the

regional dynamics, microphysics, and thermodynamics of the atmosphere prior to running comparison studies between low and high biomass burning years.

Emissions scaling factors - please see response to reviewer 1.

We have added additional comparisons to observations in the Supplemental materials, specifically for cloud cover and precipitation, which show that the model is reproducing the main features of the climate in the region.

Major Comment 2: Similar to a comment made by Reviewer 1, isn't it a rather strong (and incorrect) assumption that BC and OC are lumped into one species, given their different properties? GFED3.1 emissions are provided in terms of vegetation type but it appears that an average SSA is used for all emissions. As a result, the model isn't adequately representing the varied aerosol composition that occurs due to the different vegetation types from the central Amazon down to the Cerrado. The AERONET inversions that you show in Figure 4d support that a single aerosol composition doesn't make sense if the area of study is represented by the relatively large black square in Figure 5. I believe that Ten Hoeve et al. 2016 is relevant to reference here (http://onlinelibrary.wiley.com/doi/10.1002/2015GL066873/full). Figure 2 in that paper shows that changes in the aerosol composition will lead to changes to the impact of aerosols on cloud fraction. If the aerosol composition was allowed to vary, the resulting impact to cloud properties may be different.

Please see response to reviewer 1.

Major Comment 3: The study a few times refers to variability in deforestation. The abstract specifically states, "This study therefore provides an insight into how variability in deforestation and biomass burning emissions may contribute to the South American climate, ..." The way that sentence (and others that mention deforestation in the manuscript) reads makes it sound like the study performs experiments on the effect of deforestation on land-atmosphere interactions through changes to the land surface in the model. Another example is Page 3 Line 2. I believe this is misleading.

Reddington et al. (2015) show that there is a clear positive relationship between deforestation, BBA emissions, and AOD. Therefore we consider the impact of varying emissions to be reasonably related to the impact of varied deforestation rates. However, we have reworded several instances of the description of this relationship to make it clearer that we are not actually representing deforestation in the model, e.g. the abstract now reads, "This study therefore provides an insight into how variability in deforestation, realized through variability in biomass burning emissions, may contribute to the South American climate…"

Changed in the manuscript. Wording has been changed at two points in the introduction, abstract, and conclusion.

Major Comment 4: The "impacts of the monsoon" section is long and can be significantly shortened, especially considering that "within the constraints of the experiments performed so far, it is difficult to suggest how much, and what kind, of an effect there may be (typo) on the monsoon as a result (typo) of the biomass burning." Because there is not a strong signal, I would keep the discussion of this to a minimum. For instance, I got lost between Page 23, Line 9-24 when Figure 17 was discussed, and then again discussed on Page 25, Lines 14-26 after Figures 18 and 19 were discussed. It

seems like this entire section could be consolidated. Furthermore, I would have expected to see some comparisons of your results to other studies that have already modeled the effect of biomass burning on the monsoon, such as Zhang et al. 2009.

We have responded to a similar comment from Reviewer 1 on the monsoon discussion, and have made the alterations to significantly reduce and improve this section as both reviewers have suggested.

(From Rev. 1 response: "We acknowledge that there is too much weight given to this section and thank the reviewer for their suggestion. We have moved the figures showing similarities to previous work to the supplement, and include only a figure showing the effect of emissions in October and November in the main paper, alongside a much shorted discussion.")

Major Comment 5: Several studies have looked at aerosol cloud interactions over the Amazon, using aerosol and microphysics schemes that are more sophisticated than the bulk scheme used here. I would suggest comparing your results briefly to theirs (e.g. Wu et al., 2011, Ten Hoeve et al., 2012). However, I believe the most novel aspect of this study is that multi-year simulations are run, in turn reducing the effect of meteorology on the results. You can run the same high BB emissions over dry and wet years, warm and cool years, etc. and compare to low BB emissions over those same years. I think it would strengthen the paper to include a discussion on how the effect of different years with different meteorology either affect the H BB – L BB results, or don't.

We have added some additional comments in the manuscript on the comparisons with other publications suggested here.

Unfortunately, it appears that our description of the model setup has led to some confusion for this reviewer. The model has been run with prescribed sea surface temperatures, repeating annually, Thus we do not have the full annual variability represented as influences of ENSO and other modes of SST variability, which have been shown to have an influence on S. American regional climate etc are not captured (e.g. Marengo et al 2012). We are therefore not able to compare the wet/dry years and warm/cool years in the way suggested here. The multi-year runs are instead necessary to improve the statistics for understanding the effect of the biomass burning changes specifically which in fact necessitates removing the effects of variability in SST, rather than as a representation of the real-world meteorology over the 30 year time span. Despite having removed the SST influence, other short time scale variability remains present - this is minimised by using 30 year repeated simulations. This has been clarified in the description of the model set up (Section 2.1).

Specific Comments:
1. Line 24, Page 2: Missing comma
This has been corrected.

2. The sentence starting with "Changes in surface fluxes" on Page 3 Line 17 should have a reference
Zhang et al 2009 - reference added.

3. Please describe how the aerosol cloud interactions are parameterized in the model. There is some discussion of the aerosol scheme but not much discussion of how these

interactions are parameterized.

Fresh BBA is not considered hydrophilic. Aged BBA is considered hydrophilic and acts as a cloud condensation nuclei (CCN). Cloud droplet number concentration (CDNC) is calculated from the number concentration of CCN in the accumulation mode of BBA according to Jones et al. (1994; 2001) using a relationship based on multiple aircraft observations and assuming externally mixed aerosols. The BBA indirect effect parameterization is analogous to that of the sulfate scheme CLASSIC. CDNC is then used to calculate cloud droplet effective radius in the radiation scheme and the autoconversion rate of cloud water to rainwater in the large scale precipitation scheme (Bellouin et al., 2011). This information has been added to section 2.1.

4. Please describe in more detail how you determined the statistical significance. (Page 10, Line 10)
The significance was calculated using the Student T-test over the time series to distinguish between changes due to the emissions differences, and changes due to inter-annual variability. Text has been added to the manuscript to describe this.

5. Why do you suspect surface temperature has not changed appreciably given other surface flux changes? The percent change in Table 1 is 0.0%.
The reduction in the downwelling surface SW radiation flux is largely compensated for by the changes in the sensible and latent heat fluxes, which mean there is little change to the surface temperature. A sentence to this effect has been added to the manuscript.

6. The sentence beginning with "The difference (high-low). . ." on Page 12, Line 1 seems obvious and could be removed.
I have left the sentence in as it also clarifies that African BBA does not change between the two simulations.

7. Page 13, Line 3: What area outlined? In one of the figures?
It is the area outlined in all the plots by the black square. I have amended the manuscript text to make this clear.

8. Page 14 discusses how biomass burning reduces deep convection caused by the stabilization of the atmosphere, reduction of surface fluxes, etc. However, many studies have shown a destabilization of the atmosphere above the aerosol layer due to heating at the aerosol layer, leading to increased convection above the aerosol layer. If you look at a cross-section of cloud water, do you see increases above the aerosol layer?
The mass fraction for the cloud liquid water shows a reduction above the aerosol layer, so we are not seeing increased moisture above the aerosol layer.

9. I believe there is not enough evidence to make the statement on Page 14:
". . .suggesting that the reduction in cloud fraction may be due predominantly to this mechanism." How do you know if the reduction of cloud fraction is due to the reduced deep convection and in turn reduced cloud top anvils, or simply due to cloud burn-off of cumulus at the aerosol layer? Each effect impacts a different type of cloud. I believe

further investigation is required to ascertain the source of the cloud fraction changes.
The deep convection difference plot implies that there is a reduction in the deeper convection in the model in the high emissions case, and we are suggesting that this mechanism applies specifically to the reduction in the cloud fraction at heights of 9-12 km. This has been clarified, so that this is the implication for high cloud, and that the burn-off at the aerosol layer is likely to to be responsible for the reduced cloud fraction where cloud and and aerosol are co-located.

10. There are no units included in the caption of Figure 8.
This has been corrected for BL height, the other quantities shown are dimensionless.

11. Please reword the sentence on Page 19, Line 3 starting with "Within". Confusingly worded as written.
The sentence has been re-written to clarify the meaning.

12. Similar to Major Comment 4 above, Figure 18 a,b,d,e,g,h don't add much value because you can't see the difference between these two simulations easily. Perhaps some of these figures could be moved to the supplemental. Same with Figure 19.
We agree with this suggestion and have moved some figures to the Supplement, and re-organised others to make the differences clearer, as part of the changes to Section 4.

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The Effect of South American Biomass Burning Aerosol Emissions on the Regional Climate

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Abstract. The impact of biomass burning aerosol (BBA) on the regional climate in South America is assessed using 30 year simulations with a global atmosphere-only configuration of the Met Office Unified Model. We compare two simulations of high and low emissions of biomass burning aerosol based on realistic interannual variability. The aerosol scheme in the model has hygroscopic growth and optical properties for BBA informed by recent observations, including those from the recent South American Biomass Burning Analysis (SAMBBA) intensive aircraft observations made during September 2012. We find that the difference in the September (peak biomass emissions month) BBA optical depth between a simulation with high emissions and a simulation with low emissions corresponds well to the difference in the BBA emissions between the two simulations, with a ~~70~~ 71.6 % reduction from high to low emissions for both the BBA emissions and the BB AOD in the region with maximum emissions (defined by a box of extent 5-25° S, 40-70° W, used for calculating mean values given below). The cloud cover at all altitudes in the region of greatest BBA difference is reduced as a result of the semi-direct effect, by heating of the atmosphere by the BBA and changes in the atmospheric stability and surface fluxes. Within the BBA layer the cloud is reduced by burn-off, while the higher cloud changes appear to be responding to stability changes. The boundary layer is reduced in height and stabilised by increased BBA, resulting in reduced deep convection and reduced cloud cover at heights of 9-14km, above the layer of BBA. Despite the decrease in cloud fraction, September downwelling clear-sky and all-sky shortwave radiation at the surface is reduced for higher emissions ~~(by 13.79~~ by 13.77 $\pm$0.39 W/m^2 clear-sky ~~, 7.42~~ and 7.37 $\pm$2.29 W/m^2 all-sky~~)~~, whilst the upwelling shortwave radiation at the top of atmosphere is increased in clear sky by ~~3.33~~ 3.32 $\pm$0.09 W/m^2, but decreased by ~~-1.32~~ -1.36 $\pm$1.67 W/m^2 when cloud changes are included. Shortwave heating rates increase in the aerosol layer by 18% in the high emissions case. The mean surface temperature is reduced by 0.14 $\pm$0.24 $^\circ$C and mean precipitation is reduced by ~~15~~14.5% in the peak biomass region due to both changes in cloud cover and cloud microphysical properties. If the increase in BBA occurs in a particularly dry year, the resulting reduction in precipitation may exacerbate the drought. The position of the South Atlantic High pressure is slightly altered by the presence of increased BBA and the strength of the southward low level jet to the east of the Andes is increased. There is some evidence that some impacts of increased BBA persist through the transition into the monsoon, particularly in precipitation, but the differences are only statistically significant in some small regions in November. This study therefore provides an insight into how variability in deforestation~~and~~, realized

through variability in biomass burning emissions, may contribute to the South American climate, and consequently on the possible impacts of future changes in BBA emissions.

1 Introduction

Land management practices in South America designed to increase available land for agriculture and pasture and increasing urbanization have resulted in deforestation altering an estimated 18% of the original forest area (Artaxo et al., 2013). The biomass burning aerosol (BBA) emissions from fires tend to be largest where there is rapid deforestation (e.g. south-east Amazonia), lowest in the tropical forests in central Amazonia where the density of the forest canopy and larger amounts of moisture generally prevent fires, and areas where the fires occur in already cleared agricultural and pastoral land tend to have lower fuel loads and result in reduced fire emission per unit area compared to areas of rapid deforestation (Reddington et al., 2015; DeFries et al., 2008). Reddington et al. (2015) show that there is a clear positive relationship between deforestation, BBA emissions, and aerosol optical depth (AOD).

The biomass burning aerosols (BBA) absorb and scatter radiation, and affect the surface fluxes and atmospheric stablity. BBA also increase the concentration of cloud condensation nucleii (CCN) affecting the formation and lifetime of clouds (Koren et al., 2008; Sena et al., 2013; Koch and Del Genio, 2010). They consist largely of carbonaceous material, with a relatively low single scattering albedo (SSA) indicating they are more absorbing than e.g. sulphate aerosols. There is a direct effect on the radiative budget from both scattering and absorption (Charlson et al., 1992), and the absorption results in atmospheric heating which, together with the reduced solar radiation reaching the surface, changes the stability of the atmosphere. Heating of the atmosphere where aerosols and clouds are co-located (in altitude) is predicted to result in cloud cover changes as cloud 'burns off' or is prevented from forming due to the stabilisation of the atmospheric profile. This process has been termed the semi-direct effect (Hansen et al., 1997; Koren et al., 2008); although other studies have pointed out that the semi-direct effect could have the opposite tendency, for instance if increased atmospheric stability favors the persistence of stratocumulus (Johnson et al., 2004). The overall aerosol-cloud interaction is however complex, with the semi-direct effect depending on the relative heights of the aerosol and the clouds, the type of cloud and the regional dynamics e.g. convergent or divergent flow (Koch and Del Genio, 2010). The particles of smoke are also predicted to act as cloud condensation nucleii, (Spracklen et al., 2011), changing the size and number of cloud droplets resulting in changes to the reflectivity and lifetime of the clouds, referred to as the indirect effect (Twomey, 1974; Albrecht, 1989). Effects of BBA on convection and cloud formation characteristics can result in changes in precipitation (Gonçalves et al., 2015), which in turn will change hydrological processes, (Koren et al., 2004). Furthermore, changes in the proportions of direct and diffuse radiation at the surface will affect photosynthesis and net primary productivity (Rap et al., 2015). Koren et al. (2008) investigated the effect of BBA on cloud formation and lifetime and suggested that the stabilisation of the lower atmosphere, and the reduction in fluxes from the surface can inhibit the formation of high and deep convective clouds, despite the possible destabilisation of the higher atmosphere due to the increased heating of the atmosphere at lower levels. This effect is dependent on the initial cloud cover fraction however, as a lower initial cloud cover permits more solar absorption and increases the aerosol heating effects. The BB AOD is also a factor, with the

suggestion that at low(high) BB AOD the indirect effect is more(less) important than the semi-direct effect (Ten Hoeve et al., 2012). Feingold et al. (2005) used Large Eddy Simulation modelling for biomass burning in Amazonia to show that that where the BBA was at the cloud formation layer, this would act to reduce cloud fraction, but BBA at lower levels may tend to either increase or decrease cloudiness. However, they also found that surface sensible and latent heat fluxes are sufficient in themselves to reduce cloudiness.

Assessing the relative importance of these various effects is crucial to understanding the overall impact of BBA on the regional climate, but there is some uncertainty in how to treat and describe aerosol properties in climate models that can affect the results of such studies. Our approach uses new observations of aerosol optical properties, and compares two different scenarios, a high BBA emission experiment with a low BBA emission experiment, so that we are considering changes due to decadal time scale variability in emissions (rather than a comparison of the regional climate with BBA to one without BBA). This provides some insight into how changes in deforestation practices, which are positively related to BBA emissions and BBA AOD (Reddington et al., 2015), and the resulting changes in the characteristics of the BBA over time might affect the regional climate.

The climate of S. America shows considerable variability, due to its large latitudinal extent (12° N to 53° S) covering tropical, sub-tropical and extra-tropical climate zones. The Andes also produce large east-west variation, compounded by the change in the east-west width of the continent and the differences between the temperatures of the oceans, with the south-western Atlantic being warm, and the south-eastern Pacific being cool (Garreaud et al., 2009). In the tropics the Intertropical Convergence Zone corresponds to an east-west belt of low pressure and low-level convergence of the trade winds, resulting in an area of high annual mean precipitation which is largely produced by deep convective clouds. The annual precipitation shows a seasonal cycle, with austral winter (JJA) maximum rainfall in the north of the continent. Towards the end of October the convection shifts southwards, so that the austral summer is characterised by heavy precipitation from the southern Amazon basin to northern Argentina. During the austral autumn (MAM) the maximum precipitation moves back to the north. This seasonal pattern is considered by some to be monsoonal (Vera et al., 2006; Marengo et al., 2012), although it does not exhibit the reversal in low-level winds seen in other monsoon systems. The S. American monsoon generally has an onset in October, but the exact timing is variable, and geographically dependent, with an extension of the rainy area in the northwest of Amazonia down to southern Amazonia (Zhang et al., 2009). Generally there is an increase in precipitation from the NW to the SE from central America to the SE Amazon area, with the largest changes in the central Amazon area. Changes in the surface fluxes, with increases in surface radiation and sensible and latent heat flux are considered to be initators of the monsoon (Zhang et al., 2009). As the monsoon progresses, surface (sea level) pressure is expected to reduce over the S. Atlantic, while the sub-tropical high in the S. Atlantic is displaced eastwards and weakens (Marengo et al., 2012). Increased convection moves from down from the NW to central Amazonia and Brazil, while the circulation pattern at 850 hPa changes from northerlies to northwesterlies (Raia and Cavalcanti, 2008) in the SW part of Amazonia, and in E. Brazil from easterlies to northeasterlies following the displacement of the S. Atlantic high. Close to the mouth of the Amazon large scale northerly anomalies, and the reduction of the zonal component of the trade winds are expected as part of the transition to the monsoon (Marengo et al., 2001).

The South American Biomass Burning Analysis (SAMBBA) project was designed to use ground-based and aircraft observations of S. American biomass burning aerosols to investigate their impact on climate. It involved a consortium of international instutions, led by the UK Met Office, and the National Institute for Space Research (INPE) Brazil, in partnership with the University of Sau Paulo, and seven universities in the UK (Exeter University, Leeds University, Manchester University, University of Reading, University of East Anglia, University of York, King's College London). The observational flights were conducted in September 2012 over the Amazonian region and were coordinated with ground measurements (Allan et al., 2014; Brito et al., 2014; Marenco et al., 2016). The flights were designed to measure aerosol properties, the atmospheric chemistry, and the clouds, meteorology and radiation budget over Amazonia. The modelling presented here is part of the complementary effort to use the flight campaign observations results to refine BBA properties in global models and to ascertain the effects of these aerosols on regional climate.

In this article we test the sensitivity of the (regional) South American climate to realistic high and low BBA emission scenarios using aerosol properties constrained by aircraft campaign measurements. The main biomass burning months are August and September, so the results discussed in this paper focus on the changes in climate in September where the effects of the BBA on the regional climate are likely to be greatest, with a particlular emphasis on cloud changes, the semi-direct effect, and changes in atmospheric stability which impact cloud changes. Finally, we also briefly examine the influence of changing emissions of BBA on the S. American monsoon onset. Section 2 describes the methodology and model setup, Section 3 describes the results for the September biomass burning season, Section 4 focuses on the impact on the monsoon, and Section 5 discusses the results and their significance.

2 Methods

2.1 Model Setup

Global climate model simulations were performed with the Met Office Unified Model HadGEM3 GA3 (Hewitt et al., 2011) at a resolution of N96 (1.25 degrees by 1.875 degrees) with 85 vertical levels. Simulations were run ~~over~~ for 30 years, ~~with a~~ using annually repeating prescribed sea surface temperatures in order to minimise short time-scale variability and improve the statistical analysis. A spin up period of one year was used. Sea surface temperatures and sea ice were prescribed using data from HadISST (Rayner et al., 2003) using monthly means over 1997-2011. Greenhouse and other trace gases are fixed at levels representative of 2000, identical to (Shaffrey et al., 2009). Ozone is a seasonally varying two-dimensional latitude-height field from (Randel and Wu, 1999). The cloud scheme used was the PC2 scheme (Wilson et al., 2008a, b). Monthly emission periodic climatologies for non-BBA are used, including the 2-D sulphur cycle, black carbon and organic carbon from fossil fuel burning, from the CMIP5 dataset (Lamarque et al., 2010) with monthly means representing 2000-2010. Biogenic secondary organic aerosols are represented by an AOD climatology. The atmosphere was free running.

Aerosols were simulated by the Coupled Large-scale Aerosol Scheme for Simulations in Climate Models (CLASSIC), a mass-based ('bulk') aerosol scheme representing sulfate, fossil-fuel soot (black carbon), fossil-fuel organic carbon, biomass burning aerosol, sea salt and mineral dust aerosol species, where the physical and optical properties of each are specified, and
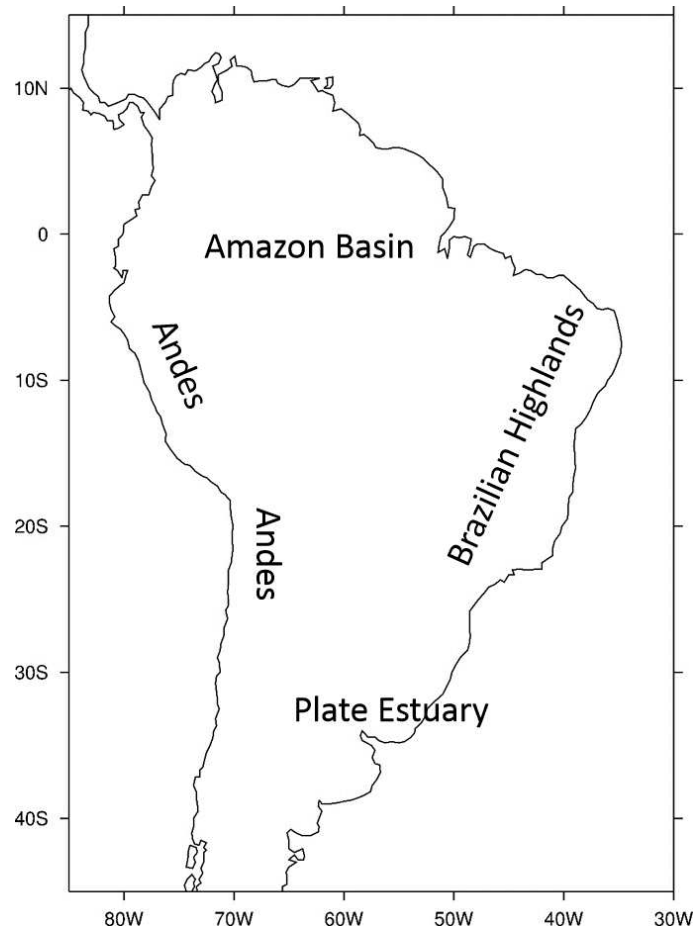
Figure 1. Map of S. America with features referred to in the text marked.

are externally mixed. A full description is given in the appendix of Bellouin et al. (2011), and Johnson et al. (2016) provide a detailed description of the BBA scheme.

The BBA scheme was originally introduced for HadGEM1 ~~(Davidson et al., 2004)~~ (Davison et al., 2004) and soon revised ~~(Jones et al., 2005)~~ for HadGEM2 (Jones et al., 2005; Bellouin et al., 2007) to use updated BBA properties based on the SAFARI-2000 aircraft field observations from Southern Africa (Haywood et al., 2003; Abel et al., 2003). ~~BBA is~~ In order to take advantage of these observations of ambient BBA available at the time, BBA was represented as a ~~single species(~~separate aerosol species, rather than as separate BC and OC components~~) with mass~~. Mass is emitted into a fresh mode, and subsequently converted into ~~a hygroscopic~~ an aged mode with an e-folding timescale of 6 h represented by an increase in mass by a factor of 1.62 (Abel et al., 2003). ~~Since OC and BC are assumed to be~~ The fresh and aged BBA modes are represented separately in CLASSIC, with different optical, hygroscopic and CCN properties for each (see Section 2.3). The fresh and aged modes correspond to different OC:BC ratios, which is justified by the fact that BC and OC are internally mixed in ~~the model,~~

~~this increase in mass~~ BBA particles. The increase in BBA mass with ageing represents an increase in the mass of OC in BBA as the aerosol ages chemically and physically from condensation of VOCs within a plume. ~~The model also allows different optical properties for~~ Although many GCMs now represent BBA as separate components comprising BC and OC, it is still advantageous to represent BBA as a single species with fresh and aged modes, ~~where in the standard setup the aged mode is less absorbing due to the decreased proportion of BC contributing to the total mass (see Section 2.3).~~ since both aircraft and remote sensing observations characterize the ambient BBA rather than the BC and OC components. Therefore although climate models which separate BC and OC may appear more sophisticated, we lack the observational constraint to support and validate their complexity, particularly in BBA source regions. In this capacity, the BBA aerosol model properties and results can still be adjusted and/or validated using the more recent SAMBBA field campaign results, which for the most part also represent the ambient BBA rather than their BC/OC components.

Since the 6 hr e-folding timescale is relatively short on a climate simulation timescale, most BBA in our simulations resides in the aged mode. ~~Aged~~ Fresh BBA is not considered hydrophilic in CLASSIC. However, aged BBA exerts an indirect effect on clouds, acting as a cloud condensation nuclei (CCN), and is converted to smoke-in-cloud-water by nucleation scavenging (analogous to sulfate aerosol in the model). Cloud droplet number concentration (CDNC) is calculated from the number concentration of CCN in the accumulation mode of BBA according to Jones et al. (1994) and Jones et al. (2001) using a relationship based on multiple aircraft observations and assuming externally mixed aerosols. CDNC is used to calculate cloud droplet effective radius for the radiation scheme and for the autoconversion rate of cloud water to rainwater in the large scale precipitation scheme (Bellouin et al., 2011). BBA is removed by wet and dry deposition. In the simulations here, we adjust the optical and hygroscopic growth properties based on observations (see Section 2.3) as we find BBA in the CLASSIC scheme demonstrates too much hygroscopic growth and not enough absorption (see Johnson et al. (2016) for more details).

2.2   BBA Emission Experiments

This paper compares the results of two 30 year climate simulations with high and low BBA emissions. Fresh BBA emissions are injected into the atmosphere as surface emissions (in the lowest model level), as well as at high levels (equally in mass across model level 3 to 20 - roughly equivalent to altitudes up to 3 km) in order to represent burning plumes ~~(which reaching higher altitudes. No plume rise routines are incorporated and burning plumes~~ are not explicitly represented ~~by the model) reaching higher altitudes~~ in the model. Recent work found that simple plume height parametrizations are sufficient in representing BBA emission heights for global climate modeling ((Veira et al., 2015)) and the vertical parameterization of emissions is also justified by the fact that CLASSIC is able to adequately represent the vertical profile of BBA in terms of shape and total column AOD compared to observations (Johnson et al., 2016).

~~Emission~~ Monthly emission datasets are taken from Global Fire Emission Dataset (GFED) version 3.1 (van der Werf et al., 2010) for BC and OC. The emissions are summed to provide total BBA emissions in terms of carbon mass, allowing CLASSIC to incorporate oxygen mass and therefore calculate BBA mass. Emissions from GFED3.1 are provided in terms of vegetation sector: forest and deforestation fires provide high level emissions, whiles savannah, woodland and peat provide surface emissions. This method does not allow for any spatial variation in BBA properties (such as optical properties) due to spatial

variations in vegetation and/or burning type. However, additional simulations were run with varied BBA absorption properties, and results indicate that these changes were small, so we consider this impact to be minimal.

In all experiments the BBA emissions are scaled up by a factor of 2, in order to produce agreement between modelled and observed AODs, a measure that has been necessary in previous modeling studies using GFED3.1 (Reddington et al., 2015;

5 Johnson et al., 2016, and references therein). Applying a global biomass burning emission scaling factor is an important assumption, but is not new to this study. Reddington et al. (2016) (their Table 2) show that multiple modelling studies have used scaling factors of up to values of 6 in the past; attempting good agreement between modelled and observed BBA AODs and particulate matter concentrations is an ongoing problem. Johnson et al. (2016) also discuss the issue, noting that many studies have had to apply emission scaling factors greater than one in order to gain agreement between modelled and

10 observed AODs and/or particulate matter measurements for BBA regions, such as Kaiser et al. (2012), Marlier et al. (2012), Petrenko et al. (2012), Tosca et al. (2013), Archer-Nicholls et al. (2016), Kolusu et al. (2015), Reddington et al. (2016). Johnson et al. (201 a scaling factor of 1.6 for CLASSIC specifically, and here we increase this to 2, which is required to be higher as a consequence of decreasing the f(RH) curve to be consistent with the SAMBBA aircraft observations (see Section 2.3). Reddington et al. (2016) find that of many model aerosol properties, hygroscopic growth factors were most important in determining the required emission

15 scaling factor. Thus we might expect to need to increase modelled hygroscopic growth in order to match models and observations of BBA; yet we find the reverse: the SAMBBA observations suggest that CLASSIC is already too hygroscopic (Johnson et al. (2016) and this work, Section 2.3). It should also be noted that there are significant differences between different emission inventories, as well as between subsequent versions of the same emission dataset (van der Werf et al., 2010; Reddington et al., 2016), which may contribute to additional adjustments required in GCM emission schemes. We encourage further work in this area - both by

20 future field work and modelling studies as well as for emission inventories - in order to reduce these important uncertainties.

In order to test the sensitivity of climate to the BBA loading within the South American region (60S to 15N and -85 to -30W) we define two experiments to correspond to high and low emission cases, based on realistic variations of emissions observed for the South American region. During 1997 to 2011, the time period covered by GFED3.1 data, the highest emission year for the South American region was 2010, while the lowest emission year was 2000. Therefore high and low BBA emission

25 experiments are defined using South American BBA emissions from 2010 and 2000 respectively. Total annual emissions for the high and low emissions experiments for the South American regions are 0.51 and 2.32 Tg respectively (including both high level and surface emissions). The geographical distribution of emissions for September 2000 and September 2010, the month of largest emissions, are shown in Fig 2. Outside of South America, BBA emissions are set to the 1997-2011 GFED3.1 mean, with monthly variations, and do not vary between experiments, in order to place the focus of the experiment solely on

30 the impact of changing S. American emissions.

2.3 Hygroscopic Growth and Optical Properties in the Modified CLASSIC Scheme

This section describes how the hygroscopic growth and optical properties for BBA are altered from the standard CLASSIC values in order to be more in line with observations, including those from the recent SAMBBA intensive aircraft observations made during September 2012 (Johnson et al., 2016; Darbyshire et al., 2017, in prep.).
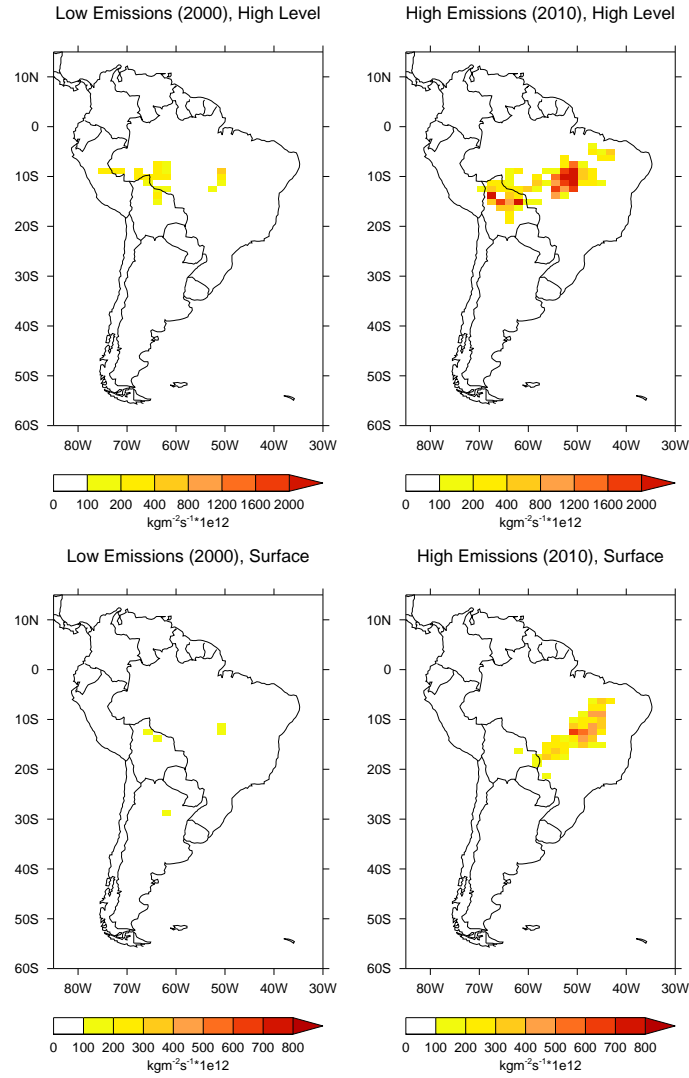
Figure 2. BBA September fire Emissions for the low (left hand side, 2000) and high (righ hand side, 2010) emission experiments as applied in CLASSIC, from the GFED3.1 dataset. Upper panels show high level BBA emissions, lower panels show surface emissions. Note the different scales between upper & lower panels.

Fig. 3 shows the hygroscopic scattering growth curve (f(RH)) of BBA in CLASSIC, and Fig. 4 shows the dependence of scattering, absorption, extinction and SSA on relative humidity. Optical properties in CLASSIC are derived from aircraft
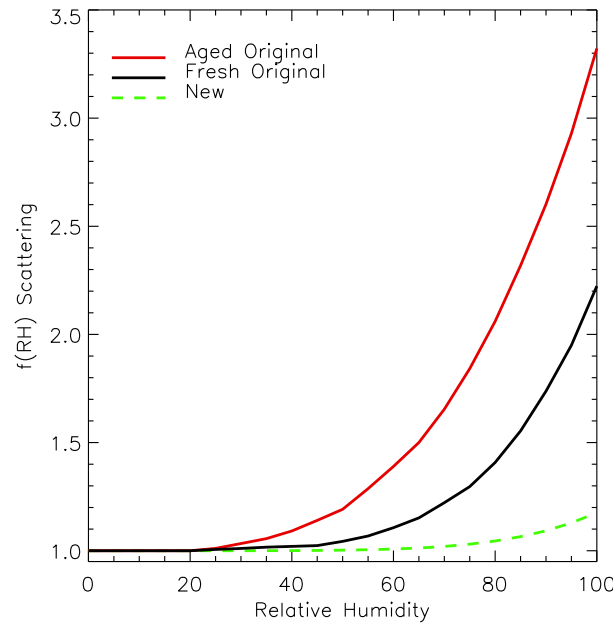
Figure 3. f(RH) scattering curves used in the CLASSIC aerosol scheme for BBA. Red and black show the standard hygroscopic scattering behaviour for fresh and aged BBA, green dashed line shows values applied in this work, taken from Kotchenruther and Hobbs (1998) for Porto Velho, Brazil.

measurements made during SAFARI-2000 of southern African BBA (Abel et al., 2003) and scattering hygroscopic growth is taken from Magi and Hobbs (2003) (~~MH03~~MH2003), also for southern African BBA. CLASSIC allows for the separate representation of optical properties and hygroscopic growth of the fresh and aged BBA modes. f(RH) values at 80% RH are 1.5 and 2.2 for fresh and aged BBA respectively (see Fig. 4), demonstrating a very strong scattering increase at high humidities.

5   Absorption in the model is not sensitive to RH (Fig. 4(b)), which is borne out by more recent measurements (e.g. Brem et al. (2012)). Since extinction is the sum of scattering and absorption, extinction in CLASSIC is also strongly sensitive to RH, as is the single scattering albedo (SSA) (Figs. 4(c) and (d)).

    However, CLASSIC is not consistent with other measurements. For example, Kotchenruther and Hobbs (1998) (KH98) performed aircraft measurements in the Amazon region around Brazilia, Cuiaba, Porto Velho and Maraba, and found much

10 lower f(RH) values for BBA in the range of 1.05 to 1.29 at 80% RH for regional haze from 4 different regions of Amazonia. Johnson et al. (2016) find that CLASSIC overestimates BBA hygroscopic growth, and therefore aerosol scattering, AOD and SSA in moist conditions. ~~Therefore in~~ In this work, we apply the f(RH) curve of ~~Kotchenruther and Hobbs (1998)~~ KH98 from Porto Velho, which was closest to the location of the SAMBBA observations, and represents the lower bound of the KH98 f(RH) curves (1.05 at 80% RH), as a weakly hygroscopic case that gives a more reasonable representation, (as indicated by
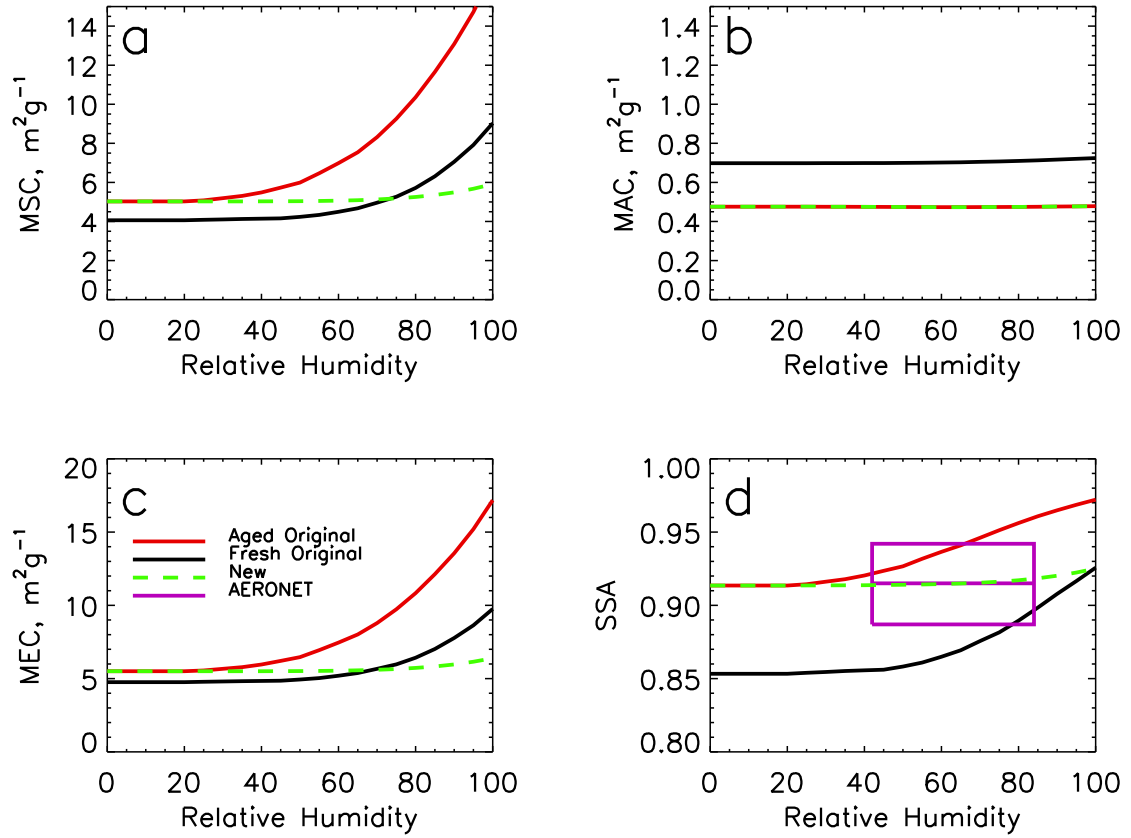
Figure 4. Optical properties used in the standard CLASSIC configuration for BBA at visible wavelengths (black: fresh BBA; red: aged BBA) and the new representations applied in this work for fresh and aged BBA (green dashed line). (a) Mass Scattering Coefficient; (b) Mass Absorption coefficient; (c) mass extinction coefficient; (d) single scattering albedo. AERONET SSA at 550nm is also shown (purple) with horizontal lines indicating long term maximum, mean and minimum (see text for details).

the green dashed line in Fig. 3) than the existing CLASSIC properties. Since this f(RH) selection represents the lower bounds of f(RH) from KH98, the AODs from the model should be viewed as a lower limit, and could still be reasonably increased by selecting f(RH) values of up to 1.29 at 80% RH.

It is not clear why the f(RH) curves of MH2003 for southern Africa and KH98 for Amazonia are so different, since both were observed with an airborne humidified nephelometer, and MH2003 do not comment on the differences. However, (Johnson et al., 2016) hypothesize that the 'regional air' classified in MH2003 may have contained a substantial amount of hygroscopic industrial sulfate aerosol, which could have behaved differently. Davison (2004) show some evidence that if combustion of peat swamps is involved, gas to particle conversion can produce high sulfate contributions in the BBA. We

anticipate new state-of-the-art observations from the recent CLARIFY project observations within the Southern African BBA plume to expand on this issue.

Fig. 4 shows the new optical properties applied in this work. Scattering values are defined to be identical to the original CLASSIC aged values at 0% RH, but increase as a function of RH according to ~~Kotchenruther and Hobbs (1998)~~ KH98 for the more realistic Porto Velho BBA observations. The RH dependence and absolute values of absorption are kept identical to the original CLASSIC data. Since extinction is the sum of absorption and scattering, extinction at 0% RH is identical to the original CLASSIC data, but is much lower at high levels of moisture due to the lower f(RH) scattering dependency.

Additionally, although Fig. 4 shows a clear difference in optical properties in original CLASSIC between the fresh and aged BBA modes, the recent aircraft observations from SAMBBA did not reveal any differences between fresh and aged BBA, except possibly for very fresh BBA close to the source, under one hour from emission (pers. comm. W. Morgan). Therefore in these experiments, since fresh BBA represents aerosol within 6h of emission, we set the optical properties of fresh and aged BBA to be identical based on the new curves in Fig. 4.

As a result, the new SSA (Fig. 4(d), green dashed line) is close to the standard CLASSIC SSA values for aged BBA at low RH, and close to the standard CLASSIC SSA values for fresh BBA at high RH. The new values are also in agreement with long term inversion data from the AERosol Robotic NETwork (AERONET) stations (purple box) in the BB region, for 6 sites (L1.5 data from Ji Prana SE, Rio Branco, Alta Floresta, Abracos Hill, Balbina, Manaus EMBRAPA) which have more than one year of data in the BB season (Aug-Oct). Horizontal lines shown in Fig. 4 represent maximum, mean and minimum SSA at 550nm (linearly interpolated between 440 nm and 675 nm) across the 6 sites. The range of RH covered by the AERONET box represents typical values encountered during the SAMBBA aircraft research flights.

A wide range of SSA values for BBA is indicated from different observations, as discussed by Johnson et al. (2016). For example, SAMBBA aircraft observations show that cerrado burning in the eastern regions produces more BC and less organic aerosol, and therefore a more absorbing BBA at 550 nm (SSA = 0.79), while forest burning in the west produces less absorbing BBA (SSA = 0.88±0.05) (Johnson et al., 2016; Hodgson et al., 2017). The range of AERONET retrievals shown in Fig. 4 is 0.89 - 0.94 (mean 0.92). Satellite-based retrievals of BBA indicate even higher SSA values (pers comm. W. Morgan). Therefore since the various observations of SSA vary greatly, an intermediate value of SSA of 0.92 at 60% RH seems reasonable for these experiments, as shown by the dashed line in Fig. 4(d). Further experiments were run with varied absorption but are not presented here. Optical properties in all of the six spectral bands covering the visible wavelengths were adjusted using the same procedure.

3   Impact of Biomass Burning Emissions in September

3.1   Introduction

September has the highest biomass burning (BB) emissions which can directly influence surface fluxes whilst in situ, so we look first at September monthly mean fields. For quantitative results we define a 'biomass burning box (BB box)' (from 5-15º S, 40-70º W), selected on the basis that this is the main area where AOD is affected by biomass burning aerosol. The

statistical significance ~~for all plots~~ is determined by a ~~t-test~~Student's T-test using the 30 year time series to identify where differences are due to the changes in the emissions, and not just inter-annual variability. We will examine the effects of the aerosol emissions on the AOD (aerosol optical depth), and the consequences of the AOD changes on the clouds, the longwave (LW) and shortwave (SW) radiation and the surface fluxes, and the surface temperature, pressure, circulation and precipitation.

5 The results are shown in Table 1, which gives the mean effect within the BB box on several variables for the high emissions case, low emissions case, and the difference; (see ~~figures for~~ Fig. 5(a) for the extent of the BB box).

Field	High	Low	Difference	% change [(H-L)/H]
AOD	0.67	0.19	0.48 ±0.01	71.6
Cloud Fraction	0.53	0.55	-0.02 ±0.01	-3.8
SW Down Surface (Clear Sky) (W/m^2)	284.42	298.19	-13.77 ±0.39	-4.8
SW Down Surface (All Sky) (W/m^2)	241.24	248.61	-7.37 ±2.29	-3.1
SW Net Surface (Clear Sky) (W/m^2)	237.15	248.63	-11.48 ±0.32	-4.8
SW Net Surface (All Sky) (W/m^2)	201.10	206.56	-5.46 ±1.93	-2.7
SW Up TOA (Clear Sky) (W/m^2)	75.32	72.00	3.32 ±0.09	4.4
SW Up TOA (All Sky) (W/m^2)	110.80	112.16	-1.36 ±1.67	-1.2
SW Net TOA (Clear Sky) (W/m^2)	327.55	330.87	-3.33 ±0.89	-1.0
SW Net TOA (All Sky) (W/m^2)	292.07	290.72	1.35 ±1.8	0.5
LW Up TOA (Clear Sky) (W/m^2)	287.07	286.54	0.53 ±0.93	0.2
LW Up TOA (All Sky) (W/m^2)	264.31	261.24	3.07 ±1.55	1.1
Sensible Heat Flux (W/m^2)	58.30	62.59	-4.29 ±0.99	-7.4
Latent Heat Flux (W/m^2)	58.86	60.64	-1.78 ±1.12	-3.0
Surface Temp (°C)	297.59	297.73	-0.14 ±0.24	0.0
Precipitation (mm/day)	1.79	2.05	-0.26 ±0.1	-14.5
Surface Pressure (hPa)	944.55	944.69	-0.14 ±0.2	0.0

Table 1. Table of September mean values for the high and low experiments and the differences between them. The means are calculated over the biomass burning box (lat. 5-25° S, lon. 40-70° W), which is outlined in Fig. 5(a).

3.2   AOD and Clouds

Fig. 5(a) and (b) shows the biomass burning AOD (BB AOD) at 0.44 μm over the 30 year HadGEM3-GA3 run for the high and low emissions case respectively. The high emissions case has a maximum BB AOD of approximately 1.6 across the central

10 biomass burning area, and values of up to 0.3 extend to the north and south. The mean value for the outlined box is 0.68 ±0.01. In the low emissions case the highest values are 0.6, with lower values of 0.1 over most of the biomass burning area; the mean in the box is 0.19 ±0.005 (see Table 1). In both cases African biomass burning results in a small transported BB AOD across the
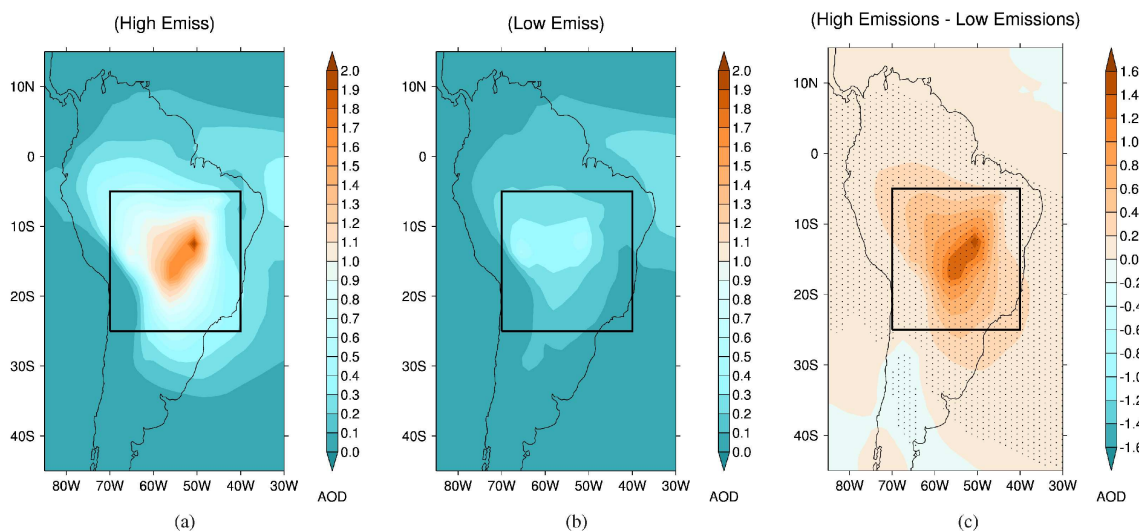
Figure 5. (a) The September mean biomass burning AOD at 0.44 μm for the high emissions experiment. The outlined box contains the area used to calculate mean values in Table 1. (b) The September mean biomass burning AOD at 0.44 μm for the low emissions experiment.(c) Plot of the difference in the September AOD between the high and low emissions experiment, (H-L). Stippling represents 95% confidence limit.

S. Atlantic, which extends to the coast of S. America. In the two model runs, the biomass emissions from Africa (and the rest of the world) are identical and are based on climatological means. The differences (high-low) in BB AOD between the two runs Fig. 5(c)) are greatest over the BB region as expected; the BB AOD transported from Africa shows no difference between the two runs, confirming that this is not the result of S. American BBA. The mean BB AOD difference in the BB box area is 0.48,

5 a reduction of 7271.6% from the high case to the low case. As discussed in the previous section, the difference in emissions is 78% suggesting that the majority of the emissions change is translated to a BB AOD change. The direct relationship between particulate emission from fire and observed AOD in South America is noted by (Reddington et al., 2015).

   In Fig. 6(a) and (b) the total September average cloud fraction for the high and low emissions experiments are plotted, showing the distribution of cloud cover. In both cases the highest cloud fractions are over the far N.W. part of the continent,

10 down into the Amazon basin. Along the east coast and into the Brazilian Highlands (centered on 15° S, 45° W) there is less cloud cover, although it increases again towards the Plate estuary (35° S, 58° W). There is also little cloud over the Andes, but a substantial fraction over the eastern edge of the Andes mountain range, and high cloud over the Caribbean area (12° N, 47° W). In Fig. 6 (c) the change in cloud fraction between the high and low emissions case is plotted - the stippled areas denote a confidence level of 95%. The cloud fraction is reduced by 0.05 in much of the biomass burning area (3.8% averaged

15 over the BB box), although there is a substantial effect to the north-east of the main AOD difference (Fig. 5). The reduction in cloud would be consistent with semi-direct effects found in other modelling studies, whereby increased atmospheric heating
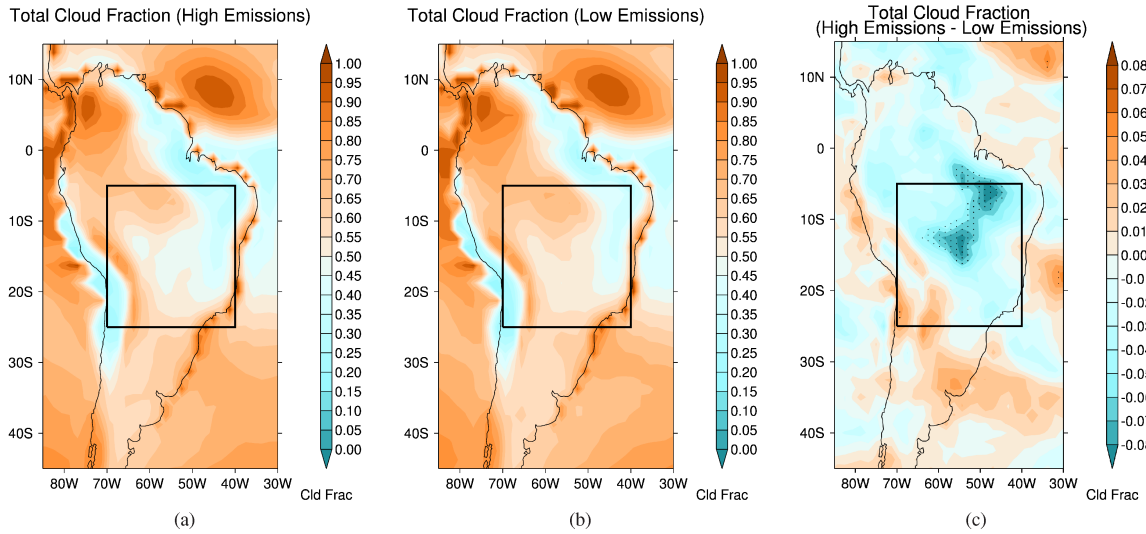
Figure 6. (a) The September mean cloud fraction for the high emissions experiment.(b) The September mean cloud fraction for the low emissions experiment.(c) Plot of the September difference in the cloud fraction between the high and low emissions experiment, (H-L). Stippling represents 95% confidence limit.

can reduce convective activity and burn-off the clouds within the aerosol layer (Koch and Del Genio, 2010). Outside of the area with high AOD differences higher emissions appear to result in a slight increase in cloud fraction in the area to the east of the Andes and just north of the River Plate valley (34° S, 55° W); however the changes in these areas are not statistically significant at the 95% confidence level.

5  The profile of cloud fraction with height ,(averaged over the area outlined in Fig. 6(a)), is shown in Fig. 7 for the high and low emissions cases. The biomass burning burden profiles are shown for comparison. Cloud layers are evident at about 1 km, 4.2 km, and the presumed outflow from deep convective clouds at 9-14 km. Despite September being the dry season these clouds were frequently observed from the aircraft during the SAMBBA aircraft campaign (Marenco et al., 2016).

  In general the low emissions case has more cloud at all levels, with the most marked differences in the high cloud amount at

10 9-14 km, and the mid-level cloud at 3-6 km. Cloud changes below 2 km are small, in part because cloud cover at these heights is minimal. Koren et al. (2004) suggest a reduction in boundary-level clouds can occur where aerosols stabilise the boundary layer and cool the surface, since the supply of water from the forest canopy is reduced. Where the aerosol and cloud are at the same height, i.e. below around 4 km, we would expect the reduction via the semi-direct effect to be strongest as the heating of the atmosphere due to the presence of absorbing aerosol promotes cloud evaporation (Koch and Del Genio, 2010). However

15 we see a similar magnitude of cloud reduction for the medium level (3-5 km) and the high clouds at 9-14 km, where the aerosol burden is much lower. A likely mechanism for this reduction in medium and high cloud cover would be the stabilising of the atmosphere, due to the aerosols in the lower levels heating the atmosphere but cooling the ground, stabilising the boundary
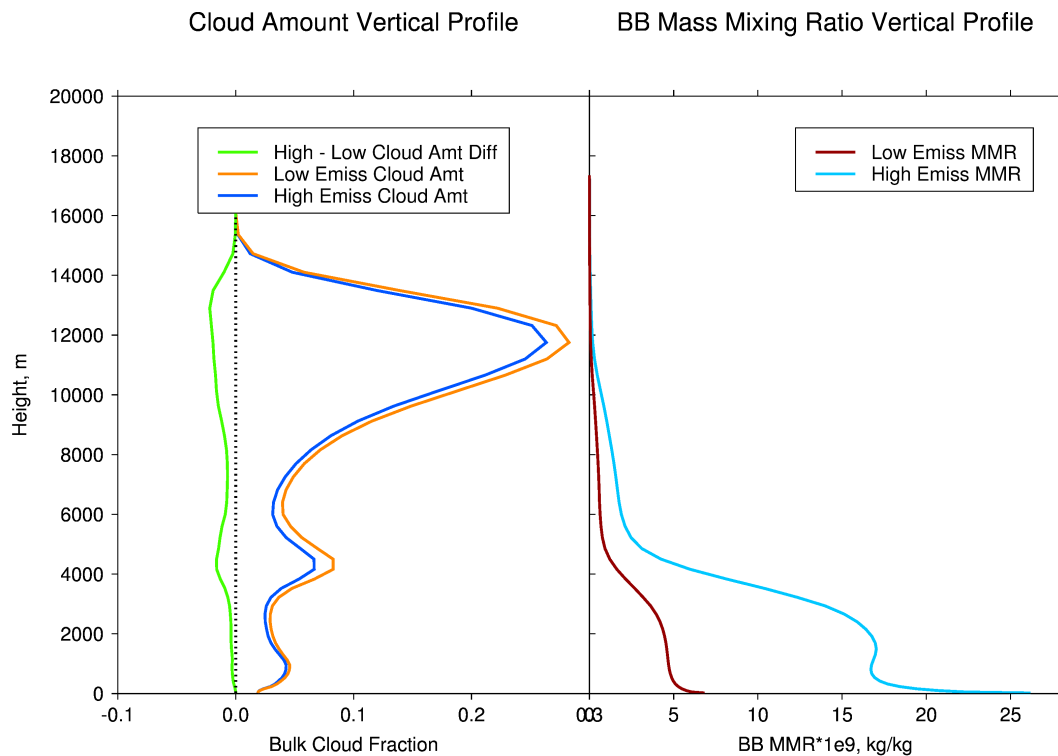
Figure 7. September mean vertical profile of cloud fraction for high emissions, low emissions, H-L compared with the vertical profile of the aerosol burden (mass mixing ratio (MMR) in Kg/Kg). (both quanities averaged over BB box area outlined in area plots).

layer, reducing its height, and thus reducing the amount of deep convection occurring in the high emissions case (Koren et al., 2008). In Fig. 8(a) the stable boundary layer diagnostic (which is defined to be set to 1 where the surface buoyancy flux is < 0.0, at each time step and each grid point; the average indicates the fraction of time in this state) shows that the high emissions case has a more stable boundary layer, especially in the areas where we see the most cloud reduction. This tends to support the explanation that cloud reduction is related to the boundary layer changes. The boundary layer height varies between 1 km and 1.8 km in the BB box, and in Fig. 8(b)the boundary layer height differences show a reduction for the higher BBA case, due to the reduction in SW radiation reaching the surface, and the reduction in sensible heat flux (Zou et al., 2017; Ackerman et al., 2000). The deep convection model diagnostic (defined to be set to 1.0 if deep convection occurs during a model a timestep, 0 if not, similar to the BL stability diagnostic mentioned above), shown in Fig. 8(c), also shows the statistically significant reduction in deep convection for the higher emissions case, across most of the main area of BBA, and also the area to the west side of the Amazon Basin. There is a dipole change in the Caribbean, where the area along the N.E. coast of S. America shows a statistically significant reduction, and just to the north there is a (statistically significant) increase for the high emissions case.

Although this is not entirely congruent with the area of highest AOD difference, it is clear that there is a significant influence of BBA on the deep convection as represented by this diagnostic, suggesting that the reduction in cloud fraction may be due predominantly to this mechanism. This change in deep convection between simulations is likely to be contributing to the high and mid-level cloud changes, as in the model some of the mid-level cloud is likely due to detrainment of deep convective cloud around the freezing level.

Where evaporation is reduced and moisture availability for cloud formation are curtailed this would also act to inhibit cloud formation (Koren et al., 2008); the relative humidity (not shown) in the high emissions case is higher at the surface (< 1 km) by around 10 %, but lower throughout the rest of the profile, with the largest difference (-7.5 %) occuring at around 5 km. With a more stable boundary layer in the high emissions case there is less turbulent transport of moisture from the surface layer. This would suggest a drier atmosphere at height is also contributing to reduced cloud formation in the high emissions case.
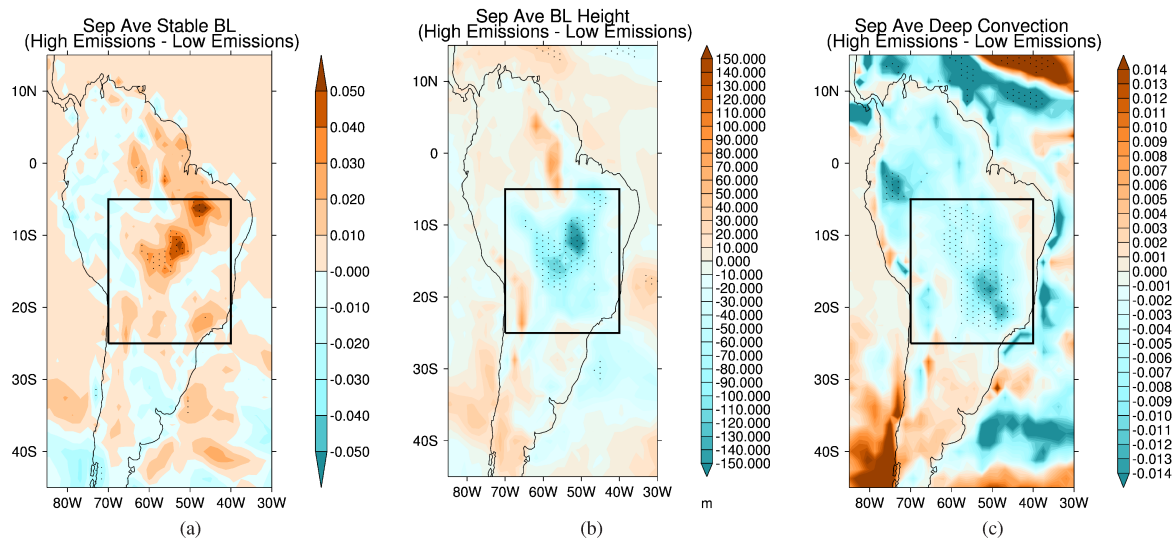
Figure 8. (a) Plot of the September difference in the boundary layer stability diagnostic between the high and low emissions experiment, (H-L). (b) Plot of the September difference in the boundary layer height between the high and low emissions experiment, (H-L) (m). (c) Plot of the September difference in the ~~Deep~~ deep convection diagnostic between the high and low emissions experiment, (H-L). Stippling represents 95% confidence limit.

Considering the indirect effect, in Fig. 9 we see a reduction in the effective radius of the liquid water drops where increasing the aerosol amount reduces the effective radius, as suggested by e.g. Warner (1968); Twomey (1977); Jiang and Feingold (2006); Rosenfeld (2000). The vertically integrated droplet concentration also increases for the higher emissions case, which is consistent with predictions that the increase in nucleation centres (aerosol particles) will increase the number of droplets. Ten Hoeve et al. (2012) and Wu et al. (2011) suggest that there is a competition between the microphysical effects and radiative
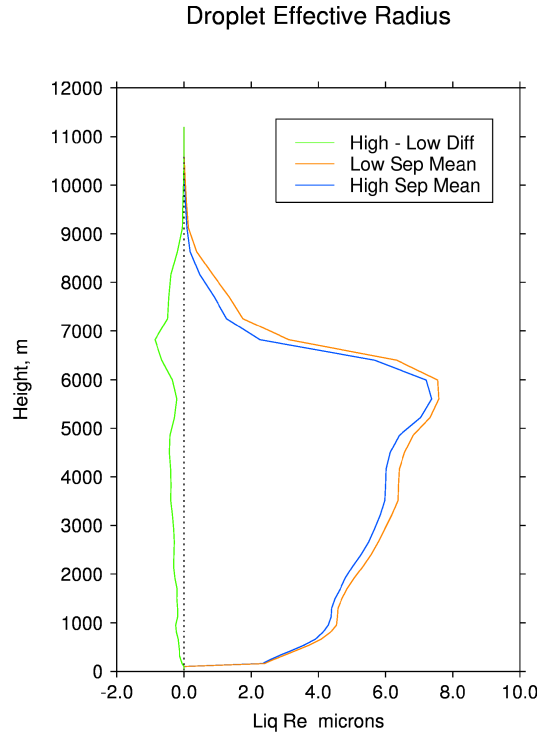
Figure 9. Vertical profile of September mean differences of droplet effective radius (microns) (averaged over the BB box 5-25° S, 40-70° W)

effects, where high AOD results in reduced cloud where the radiative effects are dominant, which is consistent with our results.

3.3   Effects on Radiation

In Fig. 10(a and b) we see the difference between the high and low emissions case in the downward SW at the surface, which largely follows the areal extent of the difference in the AOD. The results for the clear-sky (i.e. excluding all clouds) SW reaching the surface (in the BB box) from our models show the mean reduction in the September mean downwelling flux is -13.8 -13.77 ±0.39 W/m^2 (a reduction of 4.8 %) for the high emissions case compared to the low emissions case. The All-sky differences include the effect of clouds and indeed changes in the cloud fraction reduces reduce the area mean change to -7.4 -7.44 ±2.29 W/m^2, indicating that scattering by the clouds above the aerosol reduces the difference we see due to the aerosol changes alone. The competing effects of the reduction in SW at the surface due to the BBA and the increase due to reducing cloud cover control the resulting impact on the SW at the surface, and in most of the BB box area the BBA has the stronger effect. There is also a statistically significant (at the 95% confidence level) surface reduction in SW to the north of the Plate
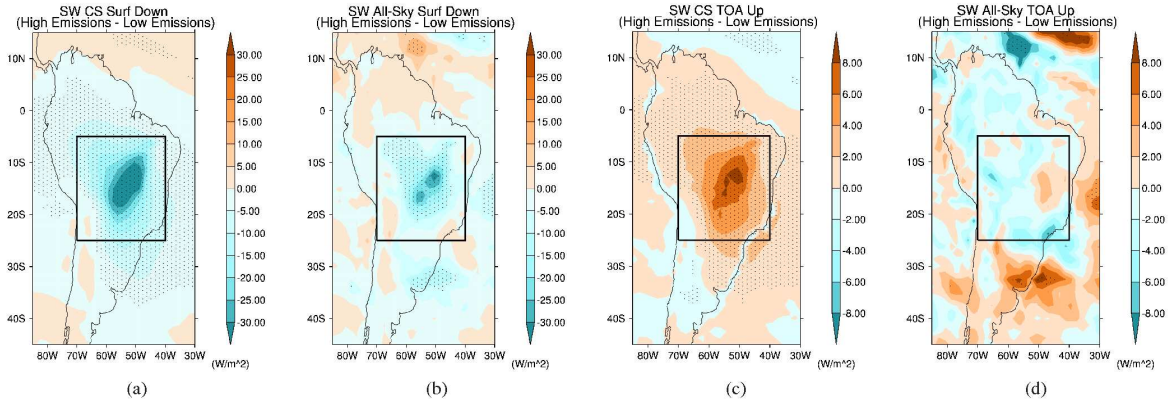
Figure 10. The September mean difference between high and low emissions case for (a) the clear sky downwelling SW radiation at the surface. (b) the all-sky downwelling SW radiation at the surface. (c) the clear-sky upwelling SW at TOA. (d) the all-sky upwelling SW at TOA. Stippling represents 95% confidence limit.

Estuary (34° S, 55° W), which we interpret as the effect of the increase of cloud in this area, as the BB AOD difference is very small in this area, while the cloud fraction increases, (see Fig. 6(a)) resulting in the reduction of SW at the surface here.

The top of atmosphere (TOA) upwelling SW radiation differences are shown in Fig. 10(c and d), where the clear-sky differences show an increase for the high emissions case in the same area as the BB AOD differences between the two experiments. This illustrates the direct radiative effect, which is stronger with higher emissions. The all-sky case is much less clear cut, as the influence of the clouds results in a predominantly negative difference. This suggests that the effect of the reduced cloud cover, and thus reduced scattering by clouds in the high emissions case, dominates over the increased scattering from the increased BBA (as seen in the ~~CS~~ clear sky case). This changes the sign of the SW radiative effect at the TOA causing a net reduction in outgoing SW in the region. These changes are not statistically significant, however.

The difference in outgoing longwave (LW) radiation at the TOA is shown in Fig. 11, where the clear-sky difference shows a generally positive change, such that the increase in aerosol results in an overall increase in the outgoing LW radiation over much of the biomass burning area. However, since the aerosol properties prescribed in the model relate to relatively small aerosol size the BBA has little effect on LW radiation directly. As the only significant changes are seen in areas outside the main biomass burning areas it is much more likely that these LW changes are related to secondary effects, for example water vapour changes. Shown in Fig. 11(c), the LW radiation changes are consistent with decreased column water vapour in the high emissions experiment, which leads to increased outgoing LW radiation at the TOA. The aerosol properties prescribed in the model relate to relatively small aerosol size therefore the effect of BBA on LW radiation is negligible. In the all-sky case, (Fig. 11(b)) the differences are significant in the main biomass burning area, but can be directly related to the changes in cloud fraction between the high and low emissions case; where the clouds are reduced, we see a greater LW upwelling at the TOA, as the effective emitting temperature is now lower in the atmosphere and warmer.
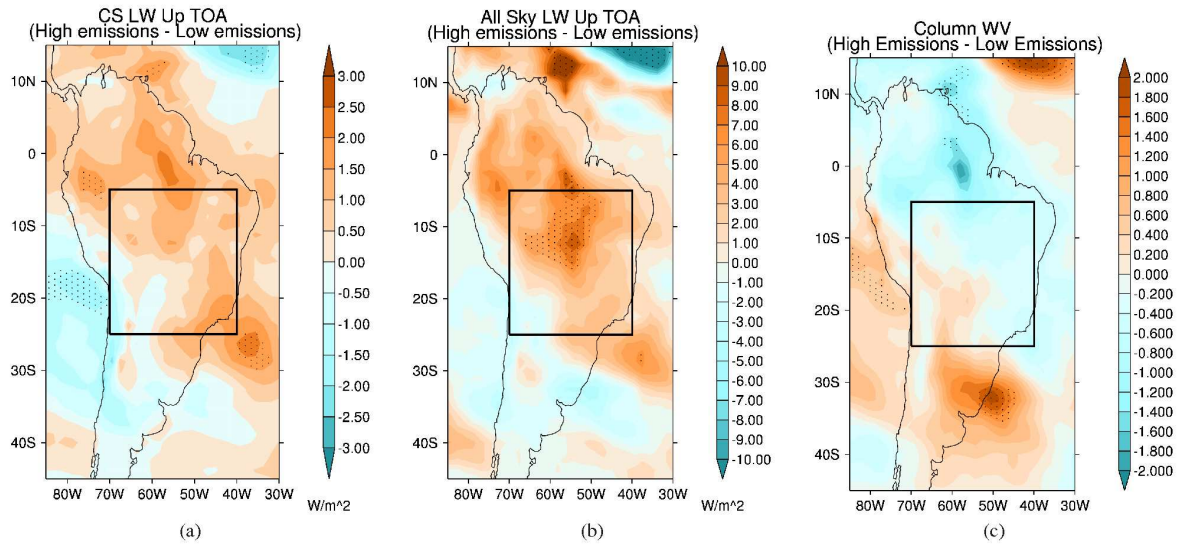
Figure 11. September mean differences (a) The difference between high and low emissions case for the clear sky outgoing LW radiation at TOA. (b) The difference between high and low emissions case for the all-sky outgoing LW radiation at TOA. (Note the colour scales for clear sky and all sky are different). (c) The difference between high and low emissions case for the column integrated water vapour.

The clear-sky SW heating rate is shown in Fig. 12(a) for the high and low emissions results. The largest difference between the high and low emissions case is below 5 km, coincident with the majority of the absorbing aerosol, resulting in an increased heating rate of the atmosphere for the high emissions compared to the low emissions case. As the BBA is absorbing (with an SSA < 1.0) it absorbs some fraction of the SW and an increase in BBA results in an increase in the heating rate. The maximum

5 heating rate also appears to be at a slightly lower altitude for the high emissions case. Above 5 km there is a much smaller difference, with a very slight negative difference at 9 km to 15 km (i.e. the high emissions have a slightly lower heating rate at this altitude).

The all-sky heating (Fig. 12(b)) rate shows broadly similar characteristics, but we see a dip in the heating rate in both cases at 500 m height, which is more marked in the high emissions case, and subsequently there is a less linear profile in both high

10 and low emissions cases. The presence of clouds provides absorption and scattering of SW radiation above the main BBA layer resulting in an increase in the heating rate at levels containing clouds, relative to the clear sky case. The SW heating rate is reduced below the cloud, as less SW radiation reaches these altitudes and thus the heating rates here are reduced. The effect of the clouds is stronger in the low emissions case, as there is more cloud here, but the differences due to cloud cover compared to the clear sky are not large. The differences between the allsky-clear sky heating rates (Fig. 12(c)), ~~illustrates~~ illustrate the

15 heating rate changes due to cloud only; beneath 4 km, clouds cause a cooling but differences between the two experiments are minimal. Above 4 km the clouds warm the atmosphere, with the extra cloud cover in the low emissions case producing a larger cloud heating rate than for the high emissions/reduced cloud case.
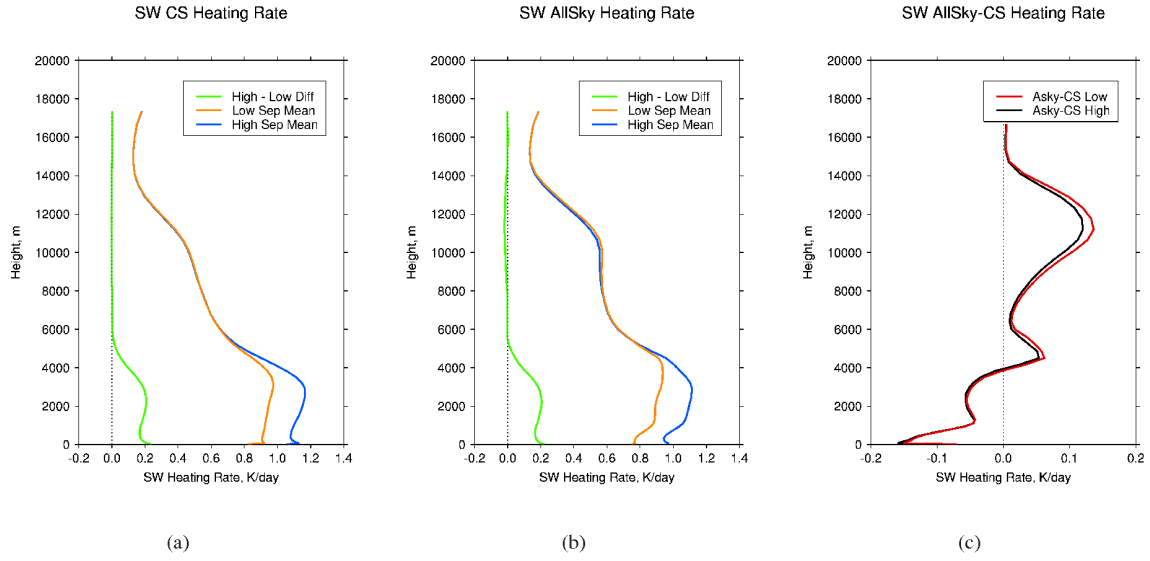
Figure 12. September mean SW heating rates (averaged over the BB box 5-25° S, 40-70° W) for high and low emissions (a) clear sky (b) all-sky (c) all sky - clear sky showing heating rate changes due to cloud only
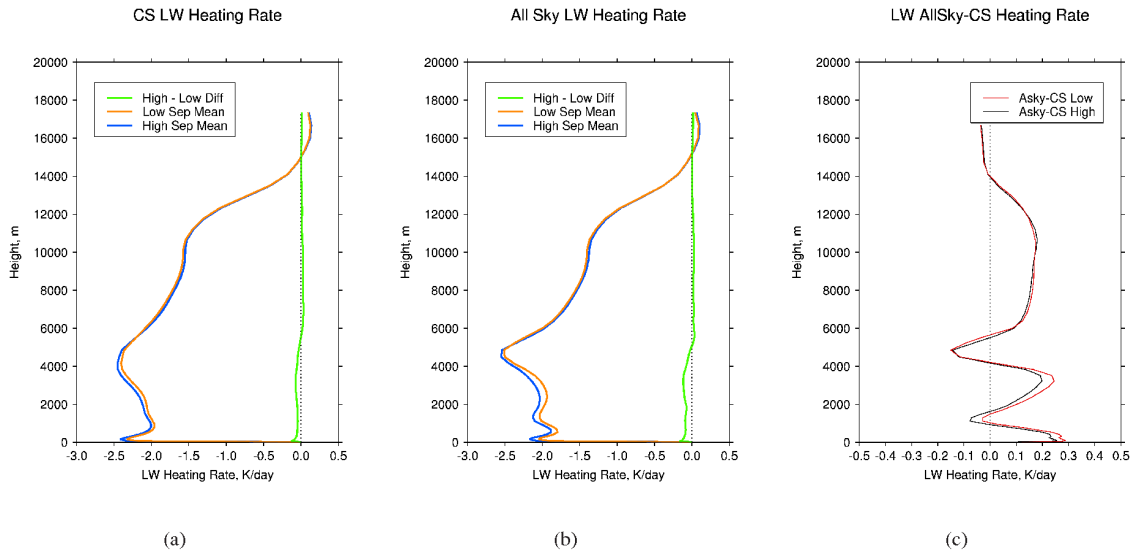
Figure 13. September mean LW heating rates (averaged over the BB box 5-25S, 40-70W) for high and low emissions for (a) clear sky (b) all sky (c) All sky - clear sky differences

In Fig. 13(a) the clear sky LW heating rates show cooling up to 15 km (tropopause), with the largest cooling of -2.5 K/day at 4 - 5 km (note the difference in scales from the SW plots). The low emission experiments show less cooling than the high emission experiment below 6 km, which then reverses from 6-14 km. In the all-sky plot (Fig. 13(b)) we see below 4 km a reduction in cloud leads to more LW cooling of the lower atmosphere. Above 4 km, the reduced cloud leads to a slight warming of the atmosphere due to the upward longwave emissions from below. Higher BBA emissions reduce the cloud cover resulting in a reduction in the absorption of radiation, and thus less LW re-emission from the clouds. There may also be an increase in LW emission due to the increased temperatures in the BBA layer (0 - 4 km). The allsky-clear sky difference plot (Fig.13(c)) shows the impact of the cloud changes alone on the heating rates, demonstrating the effect of higher emissions reducing the cloud cover, and reduced heating between the cloud layers (e.g. near the surface and at 3 km) and increased cooling within the cloud layers (1 km and 4 km), but there is very little change at higher altitudes. Within the BBA layer we can see the ~~heating rates~~ semi-direct effect of the cloud burn-off, but the higher cloud (12 km and above) appear to be responding to stability changes.

(a)   (b)
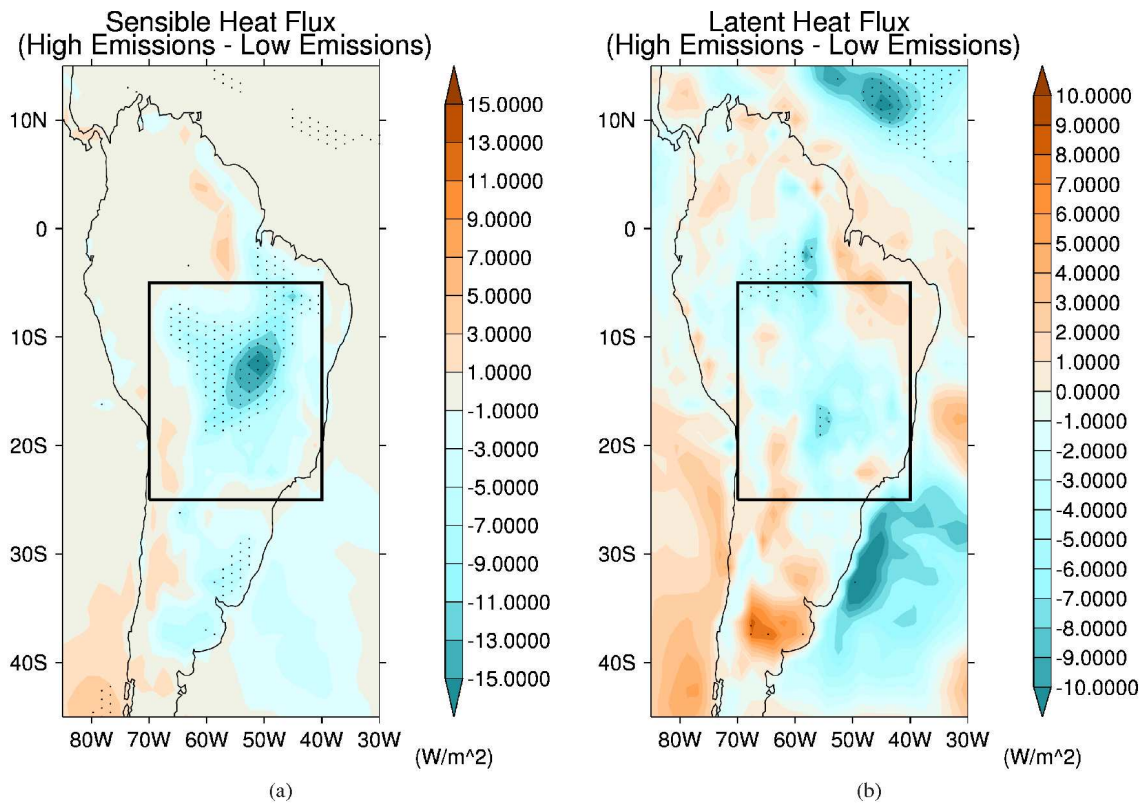
Figure 14. (a) September mean differences (high - low) for (a) sensible heat flux (b) latent heat flux. Stippling represents the 95% confidence interval.

The effects of the BBA on the sensible heat flux are shown in Fig. 14(a), where the higher emissions result in a reduced sensible heat flux, due to the reduction in SW radiation cooling the surface (c.f. Fig. 10(b)). There are also significant differences around the R. Plate estuary, which may be due to an increase in cloud cover in this area for the high emissions case which reduces the SW radiation reaching the surface, and thus also reduces the sensible heat flux. The agreement spatially with the main differences in BB AOD (see Fig. 5) is generally good, suggesting this is largely an effect of the increased BB AOD in this case. The latent heat flux differences show statistically significant reductions for the high emissions case in the area to the north of, and in the centre of, the main BB area. However these changes are not strongly co-located with the BB AOD changes and are possibly related to reductions in available moisture due to reduced precipitation and circulation changes affecting the latent heat flux, which are invesitgated in the next section. These results are consistent with those of Zhang et al. (2008).

3.4 Meteorology
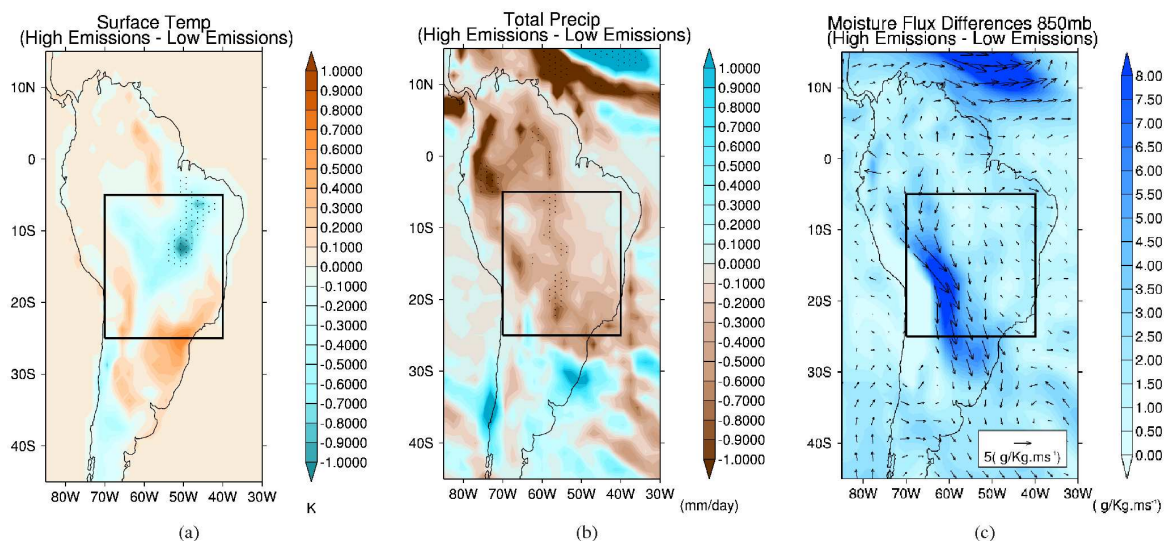
Figure 15. September mean differences (high - low) for (a) surface temperature (b) total precipitation (Stippling represents the 95% confidence interval) (c) moisture flux differences at 850 mb, coloured contours are the magnitude of the moisture flux.

There is a mean change (in the BB box) in the surface temperature between the high and low emissions runs of 0.14 ±0.23 °C, with ~~the largest~~ a statistically significant maximum decrease of approximately 0.8 °C in the north part of the BB box~~, and~~. There is a maximum increase of approximately 0.5 °C around the southern part of the Brazilian highlands, however this increase is not statistically significant, (25° S, 50° W) as shown in Fig.15(a)~~)~~. The spatial pattern here reflects the BB AOD differences in part, where the absorption and scattering of SW by the aerosol reduces the surface temperature. There are increases in surface temperature where the clouds are reduced near the southern Brazilian Highlands; here the cloud reduction allows more of the SW radiation through, and the extinction due to the BBA is somewhat lower than in the north of the box.

The competing effects of the direct effect reducing the SW radiation reaching the surface and the reduction in cloud cover increasing the SW radiation at the surface are clear, controlling the mixed geographical response of the surface temperature overall.

The differences in total precipitation are shown in Fig. 15(b), where the overall effect in much of the northern part of the continent is a reduction in the total precipitation, particularly marked in the western Amazon basin and the Caribbean. Further south we see an increase in the area just north of the River Plate (30° S, 55° W), which corresponds to the area of increase in cloud fraction seen in Fig. 6; however, this increase is not statistically significant at the 95% confidence level. The decreased aerosol in the low emissions case leads to a ~~14~~ 14.5 % increase in precipitation in the BB box with mean precipitation increasing from 1.78 mm/day (high emissions) to 2.05 mm/day (low emissions).

The decrease in precipitation seen in the high emissions experiment is consistent with the reduced cloud and latent heat flux, and the more stable boundary layer seen in this experiment. The resulting reduction in precipitation could result in a reduction in soil moisture content, partly explaining the reduction in latent heat flux shown in Fig. 14(b). Gonçalves et al. (2015) analysed rainfall data in the Amazon and suggest that the influence of biomass burning on precipitation is dependent in part on the degree of atmospheric instability. In a more stable atmosphere, BBA tends to decrease the precipitation; they also note that increasing cloud droplet number, and decreasing droplet size, would act to reduce precipitation in the absence of strong convection. In Fig. 15(c) the moisture flux at 850mb shows the increase of moisture transported by the low level jet east of the Andes, which together with the increased flux from the S. Atlantic combines to produce the increase in precipitation seen at 30° S, 50° W.
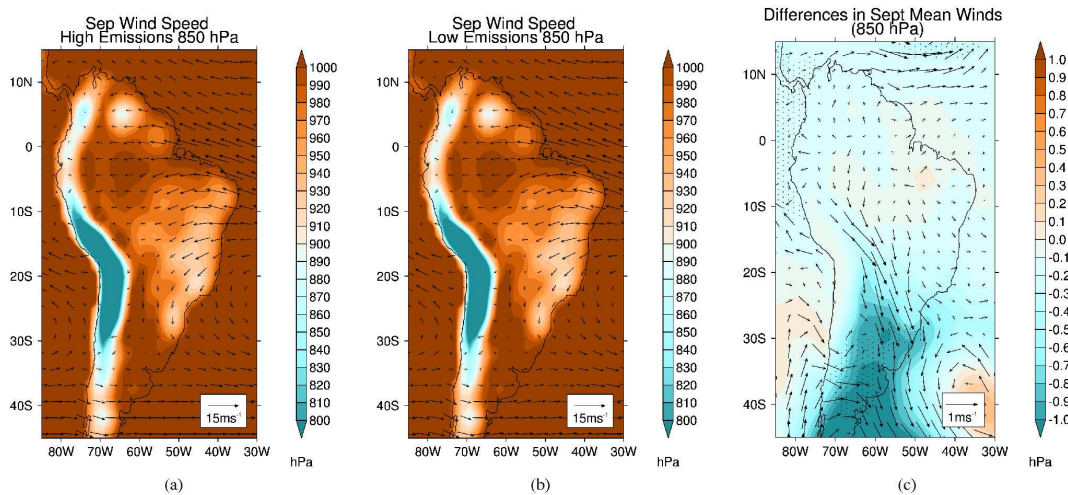
Figure 16. September mean wind circulation at 850 ~~mb~~ hPa for (a) high emissions case. Coloured contours are mean September pressure in ~~mb~~hPa. (b) low emissions case. ~~Coloured contours are pressure in mb.~~ (c) differences in pressure and wind circulation for high - low runs. Coloured contours in (a) and (b) are surface pressure and in (c) surface pressure differences in ~~mb~~hPa.

The surface pressure and 850 ~~mb~~ hPa circulation for high and low emissions are shown in Fig. 16(a) and (b). The ERA-Interim mean September surface pressure and circulation (averaged over a similar time scale) are shown in the Supplemental material (~~Fig. ?? and Fig. ??~~Supplemental Fig. 1 and Supplemental Fig. 2) for comparison, and show that in general both surface pressure and the circulation are well represented by the model, although the wind flow seems to be somewhat more zonal between 0-10° S in the ERA-Interim plot. The model results for surface pressure are broadly similar for both the high and low emissions experiments, with a high pressure area in the central Amazon basin, and low pressure to the north and west. We also see high pressure along the eastern side of the Andes, down towards the River Plate estuary, and a high pressure system in the south east Atlantic, which shows some difference in position between the high and low emissions case. The surface pressure differences (Fig. ~~15~~16(c)) show a slight increase in the Amazon basin area, but a larger decrease down in the southern part of Brazil and around the Plate Estuary. We also see a difference in the S. Atlantic, which is related to the position of the S. Atlantic high shifting between the high and low emissions case. The pressure differences are of the order of 1mb, with significant changes at the 95% confidence level in the Caribbean area and in S. Argentina.

The change in pressure patterns corresponds to the change in winds at 850 ~~mb~~ hPa. (Fig. 16(a) and (b)). The general circulation is easterly across the Amazon basin, south-easterly in the Caribbean, and tending to north-easterly to the south of the Amazon mouth. In the southern part of Brazil we see a northerly direction, turning westerly at the southern tip of the continent. Although the overall circulation ~~patters~~ patterns are similar for the two experiments, we do see differences between the high and low emissions case in Fig. 16(c), the largest effect being a strengthening of the low level jet that runs along the eastern side of the Andes, from around 10° S to 30° S, down to the Plate Estuary. Analysing the zonal and meridional components suggests that the most significant change is in the zonal component possibly ~~suggestuing~~ suggesting a change in direction as well as in strength. There is also a change in the circulation due to the shift in the S. Atlantic high pressure system, where the easterlies are weaker in the low emissions case, and have a more southward component in the high emissions case. In the Caribbean area the prevailing easterlies and south-easterlies are weaker in the high emissions case.

4   Impacts on the Monsoon

~~We investigated whether or not there was a significant impact of the BBA on the South American monsoon by comparing precipitation and circulation differences between the high and low emissions cases for the monsoon onset months of September, October and November. As we do not have model results output on a daily basis, we cannot resolve the question of whether the detailed timing of~~

Fu et al. (1999) suggest that local thermodynamical processes may be important for onset of the monsoon~~is affected by the BBA using these experiments. However, we can examine whether the effects of the August-September peak biomass burning carry through the monsoon onset in October to November, using the monthly means to compare the meteorology between the high and low emissions case.~~

~~Mean monthly circulation (a) Sept High emissions. (b) Sept Low emissions. (c) Sept differences (H-L) (d) Oct High emissions. (e) Oct Low emissions. (f) Oct differences (H-L) (g) Nov High emissions. (h) Nov Low emissions. (i) Nov~~

differences (H-L Note the difference in projection and area from previous plots) , whilst the strength of the low level jet to the east of the Andes is an important source of moisture for the subtropical convection that brings rainfall to the South of the region in the wet season (e.g. Liebmann and Mechoso (2011)). As these features appear sensitive to the aerosol emissions during September (see 3.4) we now consider whether there is any discernible difference in the transition to monsoon regime between high and low aerosol simulations. We do this in only a broad sense, since the temporal resolution of our output is not sufficient to identify a specific monsoon onset date, and in any case, the definition of onset is a matter of some debate in the literature (Liebmann and Mechoso, 2011). The transition to the wet season between September and November is broadly similar in the model as shown in previous studies (Raia and Cavalcanti, 2008; Liebmann and Mechoso, 2011; Marengo et al., 2001, 2012) comprising

4.1 Evolution from September to November

The changes in the wind circulation from September to November can be seen in Fig. **??**, with the winds at 850 mb for the two emissions cases and the differences between them shown for the three months. The overall evolution of the circulation from September to November broadly follows the predicted patterns (Raia and Cavalcanti, 2008; Marengo et al., 2001, 2012) for monsoon development in both high and low emissions cases. In October the overall circulation is similar to that for September, although there is a shift from easterlies to northerlies and north-easterlies across the Amazon basin; as we move into November this trend towards northerly and

– Shift to northerly and north-easterly winds becomes more pronounced, particularly in the western Amazon basin where by November the winds are northerlies. In the Atlantic close to the Amazon mouth we see a shift from the south-easterlies to more easterlies, a trend which continues into November. The (northerly) low-level jet along the eastern side of the Andes strengthens as we go from September to November, and the S. Atlantic high pressure system shifts westwards and decreases, with a corresponding shift in the circulation in the S. Atlantic and the S.W. coastal areas of the continent (Marengo et al., 2012). In November the changes show the clear shift from easterlies in the equatorial area in September to north-easterlies and northerlies, which exemplifies the change from zonal to wind across the Amazon basin,

– Strengthening of the northerly low level jet to the east of the Andes,

– Eastward movement and weakening of the high pressure system,

– Shift to cross-equatorial flow as discussed in Marengo et al. (2001). The N. Atlantic trade winds strengthen in the equatorial area in November, and the change in E. Brazil from easterlies in September to north-easterlies in November (Raia and Cavalcanti, 2008) is apparent, and is due to the displacement in the S. Atlantic high from September to November. The low level jet along the E. Andes becomes stronger, and in general northerlies run down the centre of the continent.

The changes in pressure from September to November (Fig. **??**) show a general decrease (in both emissions cases) overall which is most marked along the eastern edge of the S. Andes, and down towards the Plate/Salado valleys (20S,

65W down to 40S 65W). The S. Atlantic high shifts eastwards, and reduces somewhat in strength from September to November (??(a-d-g), as described in Raia and Cavalcanti (2008). In September (Fig. ??(a-c)) the pressure shows the S. Atlantic high and a S. Pacific high, on each side of the continent at 30S. We see low pressure related to the topopgraphy in the Andes, Guyana Highlands and the Brazilian highlands. In October, Fig. ??(d-f), the small high pressure system in the central Amazon shrinks slightly in size, and we see the S. Atlantic high shifting eastwards. The S. Pacific high appears to increase slightly in size, especially in the high emissions case. The surface pressure in November (Fig. ??(g-i)) shows the S. Atlantic high pressure region shrinking in size and moving further eastwards, and the S. Pacific high also shrinking slightly, There is a decrease in pressure between the N.E. coast of S. America and W. Africa, which is more pronounced in the low emissions case.

The development of the precipitation from September to November clearly shows the extension of the high precipitation amounts in the western Amazon towards the south and west, indicative of the beginning of the wet season across the central part of S. America. The September precipitation shows high precipitation in the western Amazon basinand north of the equator, and lower values throughout the rest of the continent, especially dryer in the Atacama desert and over the Brazilian Highlands. The levels outside of the western Amazon are around 7 mm, down to < 0.5 in the dryer areas. Moving to October we see the higher precipitation spreading southwards down the west coast, and across towards to the east coast in the northern part of the continent. November precipitation as shown in Fig. ??(i) shows this area of increasing precipitation moving soutwards and eastwards, although the area at the northern tip of the Brazilian Highlands and the N.W. coast remain at a similar level of precipitation as in October. The pattern of increasing precipitation from September to November we observe here is broadly in line with the predictions for the monsoon onset in this region(Raia and Cavalcanti, 2008; Liebmann and Mechoso, 2011).

4.1 Differences Between High and Low Emissions for September to November

We have already discussed the main circulation differences between the high vs. low emissions for the September case in 3.4; we noted that rather than zonal flow to the north of the low-level jet along the east side of the Andes is affected by the BBA, and the circulation in the S.E. Atlantic is altered (see Fig. ??(c)). The October differences between high and low emissions region,

– Increased rainfall over the Amazonian basin that extends southwards and eastwards moving through October and November.

These changes are shown in Fig. ??(f)), where we see little difference over the Amazon, with the largest changes along the west coast in October showing a greater northward component in Supplemental Fig. S5, where the high emissions case in the westerlies, and the circulation evident at 20-30S and 90W also shows a strengthening of the northward component in the high emissions case. Around the S. Atlantic area there is again a more northward and north-eastward tendency along the coast for the high emissions, turning to a larger southern component out at 35S, 30W - these changes are most likely related to changes

in the S. Atlantic high. The differences between the high and low cases in November are less striking although we still see the effects of changes in the S. Atlantic and there are also residual differences in the S. Pacific (Fig. ??(i)). As the position of the S. Atlantic high is affected by the aerosol emissions the changes in the circulation and thus the moisture flux in this area could be ascribed to the BBA. There is also a weakening of the easterlies at 0-10N in the atlantic area for the high emissions case, and some increase in the low level jet on the east side of the Andes, but only south of 15S, 70W; north of this point the flow is weakened in the high emissions case is used to show the mean November meteorology, exemplifying the changes described above.

The differences in Significant differences are seen in October surface pressure between high and low emissions for September (Fig. ??(c)) show a slightly higher pressure around the Amazon basin, and in the S. Pacific and S. Atlantic, although these latter two changes are most likely related to changes in the simulations across the South Atlantic and South Pacific reflecting slightly different positions of the respective high pressure systems. There is a larger change in the southern end of the continent, from 25S down to the southern tip, which is significant at the 95% confidence level. There is also a statistically significant pressure reduction along the N.W. coast andout across the equatorial pacific. The differences plot for October (Fig. ??(f)) reflects these changes, with the largest statistically significant changes in the S. Atlantic and S. Pacific. We also see statistically significant changes from the western Amazon basin down the E. side high pressure in each case, and on the east of the Andes to the southern edge of the Brazilian highlands. The other large area of statitistically significant difference is across the Atlantic between W. Africa and the N. Eastern edge of S. America. In November the difference plot (Fig. ??(i)) shows no statistical significance in the changes, but the S. Atlantic and S. Pacific changes are still evident. The changes in the rest of the continental area are small, with a switch to a positive difference (H-L emissions) in the areas of the Amazon Basin and the eastern parts of the BB box. It is clear there are statistically significant differences in surface pressure that extend into October, but the changes in November are generally smaller in magnitude and not significant.

Mean monthly total precipitation - note that blue represenst high values, brown low values. (a) Sept High emissions. (b) Sept Low emissions. (c) Sept differences (H-L) (d) Oct High emissions. (e) Oct Low emissions. (f) Oct differences (H-L) (g) Nov High emissions. (h) Nov Low emissions. (i) Nov differences (H-L Note the difference in projection and area from previous plots)

The precipitation differences between the high and low emissions cases for September were discussed in Section 3.4, where we noted an overall reduction in precipitation in the BB box and Amazon basin, and an increase to the north of the Plate estuary (Fig. ??(c)). October precipitation differences (Fig. ?? where pressure is lower in the higher emissions case, but this does not extend into November 17(b, e). We do however find a significant decrease in November precipitation 17(f)) are mixed, with increases in the Amazon Basin, and in parts of the Brazilian Highlands, and decreases in the centre of the BB box and the Gran Chaco area (centred at 25S, 60W), down to the area between the Plate estuary and the southern edge of the Brazilian Highlands. However, the only areas with statistical significance are around the areas N. and W. of the Plate estuary. The mean differences in precipitation for November are shown in Fig. ??(i), where we see the area of reduced rainfall is quite extensive, extending from the Amazon basin down the east of the Andes to the Plate estuary(35S 60W) . The areas in the NW corner of the BB box, and the E. side across the Amazon basin area in the higher emissions simulations which is consistent with enhanced transport of
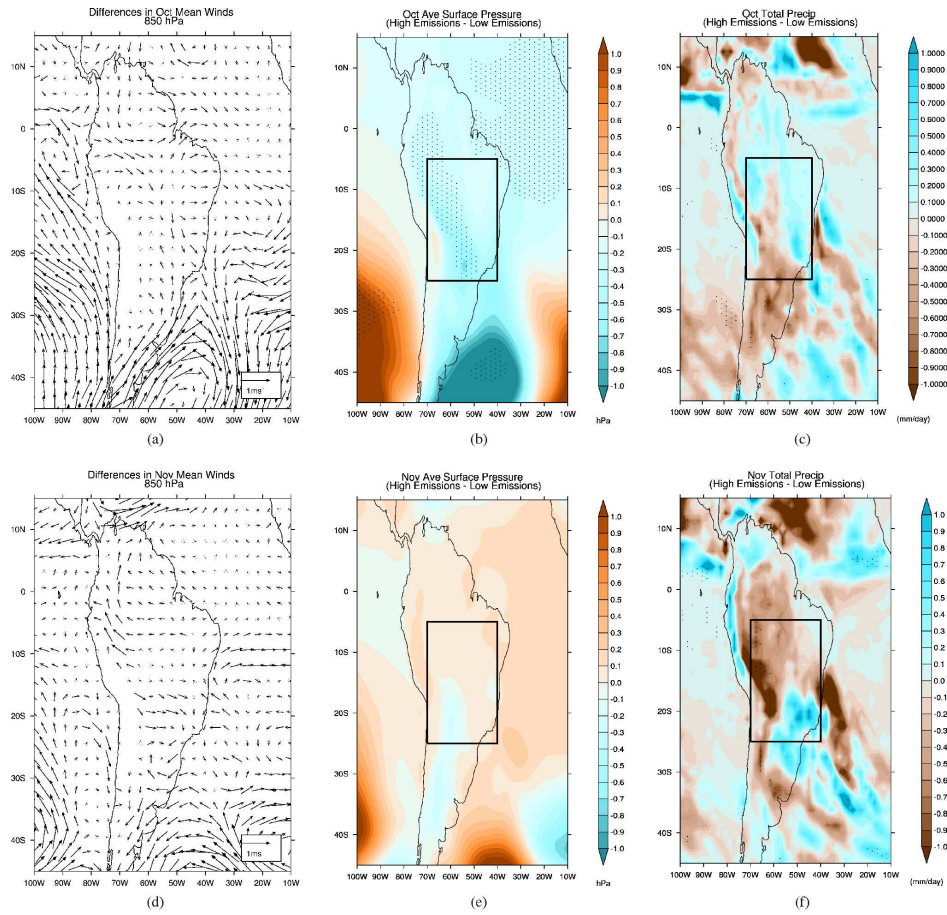
Figure 17. ~~Mean monthly surface pressure~~ Plot showing the differences in meteorological variables for October and November (a) ~~Sept High emissions~~Differences in mean circulation for October. (b) ~~Sept Low emissions~~Differences in mean surface pressure for October. (c) ~~Sept differences (H-L)~~ Differences in mean precipitation for October. (d) ~~Oct High emissions~~Differences in mean circulation for November. (e) ~~Oct Low emissions~~Differences in mean surface pressure for November. (f) ~~Oct differences (H-L) (g) Nov High emissions. (h) Nov Low emissions~~Differences in mean precipitation for November. (~~i) Nov differences (H-L~~Note the difference in projection and area from previous plots)

moisture from the Amazonian basin by the strengthened jet 16(c) on the east of the Andes ~~towards the Plate Estuary all show significant differences at the 95% confidence level, and could be related to changes in the circulation, increased convective stability and the moisture fluxes in these areas (Collini et al., 2008). We also see significant differences in the S. Atlantic area, which could be related to changes in circulation as a result of the difference in the position of the S. Atlantic high~~
5   ~~pressure system between the high and low~~ in the high emissions case. ~~Precipitation increases around the Brazilian Highlands, although this is not statistically significant at the 95% confidence level. The changes in the precipitation due to the BBA are~~

significant in a few areas, suggesting that there is a continuation of the effect of the BBA on precipitation through to November, and thus on the monsoon. Overall, there is an effecton several parameters related to the monsoon development, which could be interpreted as affecting the monsoon development. However, within the constraints of Freitas et al. (2005) examination of biomass burning in regional climate models suggested that aerosols might oppose the transition to monsoon state, with strong absorption stabilising the troposphere in the southern Amazonian region. Whilst the results in our model suggest that the experiments performed so far, it is difficult to suggest how much, and what kind, of an effect there may on the monsoon as a results of the biomass burningstrengthening of the jet east of the Andes may also have an effect, further simulations with higher temporal resolution of output would be needed to establish the mechanism by which aerosol emissions appear to affect the monsoon rainfall.

5   Discussion and Conclusions

The aim of the work described here was to investigate the impact of biomass burning emissions on the regional climate in S. America using the Met Office Unified Model HadGEM3 GA3 model. We examine this through two 30 year climate runs with BBA emissions taken from the GFED v3.1 dataset, representing low and high emission years. We adjust ambient BBA optical and hygroscopic properties based on the literature and on recent airborne in-situ measurements from the SAMBBA project. We employ a global BBA emisson scaling factor of 2 in order to generate AODs comparable to observations. Reconciling surface particulate matter concentrations and AODs for BBA between models and observations is a continuing problem for climate models and the scientific community, largely impacted by the hygroscopic activity of BBA and choice of emission dataset and version, and we urge further research in this area in order to reduce modelling and observational uncertainties.

We have found clear semi-direct effects of the biomass burning aerosol in September, with the results indicating a significant burning off and an additional effect on cloud cover from reduced deep convection, as the aerosols stabilise the boundary layer and supress surface fluxes. Changes in the cloud microphysical properties (i.e. effective radius of the droplets) are evidence for the 1st indirect effect occurring as a result of increased BBA. The changes in the SW radiation for higher BB emissions are as expected from the direct effect, with a reduction in downwelling SW radiation at the surface and an increase in outgoing SW radiation at the TOA in the clear-sky case. The all-sky (cloud effects included) case shows less of a reduction at the surface, due to the decrease in cloud cover which indicates that the BBA dominates the surface radiation SW flux while simultaneously decreasing cloud cover. The effect on the outgoing SW radiation at the TOA is more mixed. The LW radiation changes are controlled mainly by cloud changes, although WV changes induced by the BBA also contribute. Atmospheric heating is increased in the presence of more aerosol, and surface fluxes respond to the reduction in the surface SW radiation with both the sensible and latent heat fluxes being reduced. The reduced SW radiation also lowers the surface temperature, where a combination of the aerosol and the aerosol-cloud interactions causes reductions in surface temperature in areas of higher BB AOD, and an increase in areas where the cloud cover is sufficiently reduced to counterbalance the cooling effects of the BB AOD. There is a potential feedback from the reduction in SW radiation at the surface and heating by the aerosol at higher altitudes causing cloud burn-off and increased BL stability; the increased stability reduces cloud generation and leads to

a further reduction in the cloud cover. This process will break down if the increase in SW radiation reaching the surface due to loss of cloud cover dominates over the BBA effects, allowing the BL to once again destabilise (Koren et al., 2008). The mean September precipitation in parts of the BB area is significantly reduced (up to 15 %) in the BB box, with some reduction also occuring in parts of the Amazon basin, most marked towards the western edge. There is also an effect on the surface pressure and changes to the low-level (850mb) circulation, in particular the low-level jet east of the Andes and the S. Atlantic high pressure system.

The impact on the monsoon is less clear cut, however we see distinct differences in November between the high and low emissions experiments. The changes in the surface pressure and circulation, in particular the low level jet which brings moisture down from the Amazon, and the shift in position of the S. Atlantic high pressure system affect monsoon development ((Raia and Cavalcanti, 2008). There is significant reduction in precipitation along the eastern side of the Andes and around the Plate Estuary area. These changes in the precipitation due to the BBA suggest that there is a continuation of the effect of the BBA on precipitation through to November, and thus on the monsoon. We note that in order to see any possible effects on the timing of monsoon onset a finer temporal resolution in the model output would be required. A further caveat is that the model is not a fully coupled atmosphere-ocean model, so the atmospheric changes do not influence the sea surface temperature (SST) so that effects of sea surface temperature changes, in particular on the monsoon development (Marengo et al., 2001; Liebmann and Marengo, 2001), are not being modelled in these experiments.

The experiments described use emission inputs (from GFED version 3.1) for two different years in order to gauge how the climate effects differ between years with high and low emissions instead of comparing a BBA-free atmosphere with a high BB aerosol case. Our approach does tend to lessen the signal to noise in the results compared to a biomass burning vs. no biomass burning comparison, but allows us to demonstrate that significant climate differences can result from the realistic annual variations seen in the BB BBA emissions in S. America, which can be reasonably related to changes in deforestation, due to the strong positive relationship demonstrated between deforestation rates and BBA emissions ((Reddington et al., 2015)).

Author contributions. C.L.R set up and performed the model runs for which B.T.J. provided emissions files. G.D.T analysed the model run results. G.D.T. prepared the manuscript, C.L.R. wrote the model set-up sections and all authors contributed to scientific discussions and helped in writing the manuscript.

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1 Supplemental Material
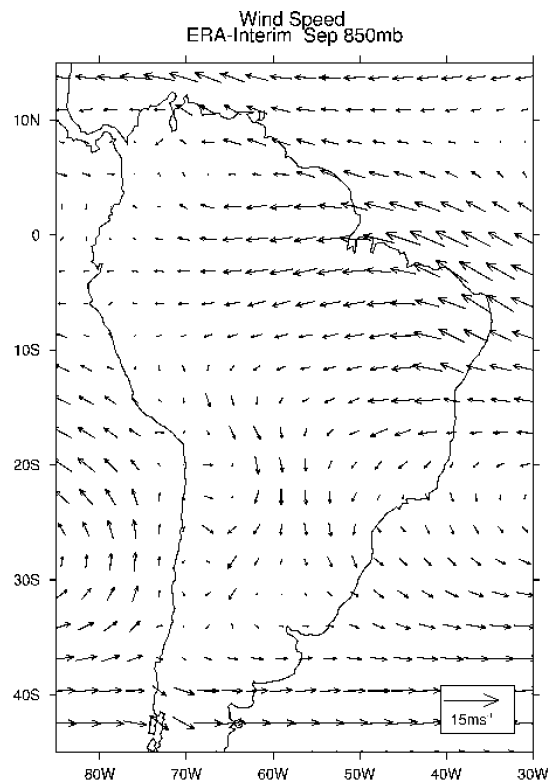
Figure 1. ERA-Interim September means over 1982-2012 for wind circulation at 850hPa.

The ERA-interim September means (1982-2012) generally compare well with the model results for the surface pressure and circulation, and although we see some differences in cloud fraction between the model and ERA-Interim for the overall cloud cover. The model tends to slightly over-estimate cloud cover in some areas, but the general spatial pattern is similar bwteen the two. The precipitation is also broadly similar, with some dicrepancies in the equatorial region, but over most of the region the values are generally similar. These comparisons are included here to demonstrate confidence in the model's ability to reproduce the broad elements of the meteorology for South America in September.

ERA-Int Sep Ave Surface PressureSep
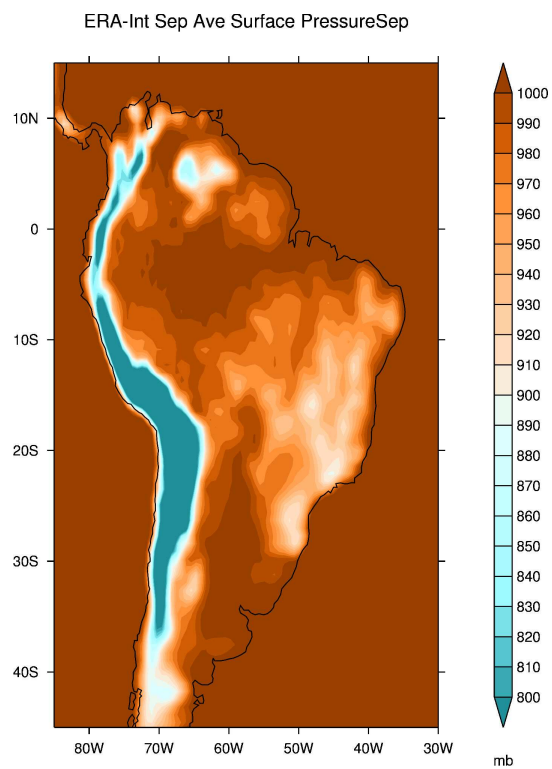
Figure 2. ERA-Interim September means over 1982-2012 for surface pressure in mb.
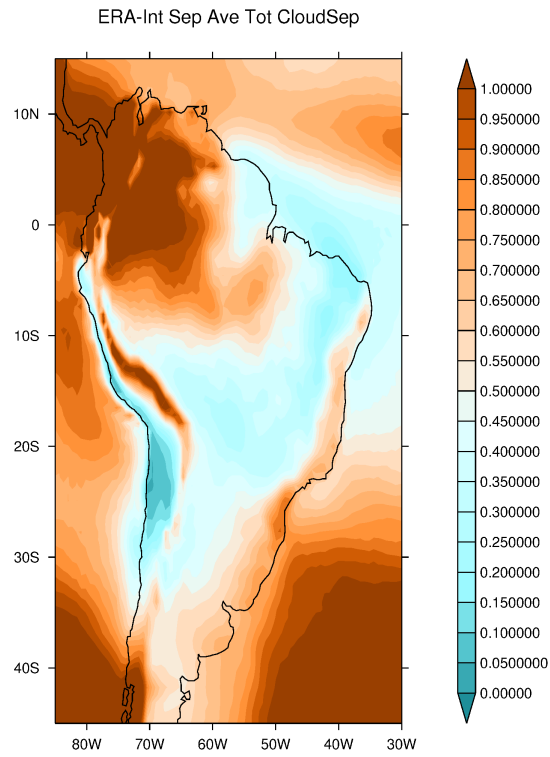
Figure 3. ERA-Interim September means over 1982-2012 for cloud fraction.
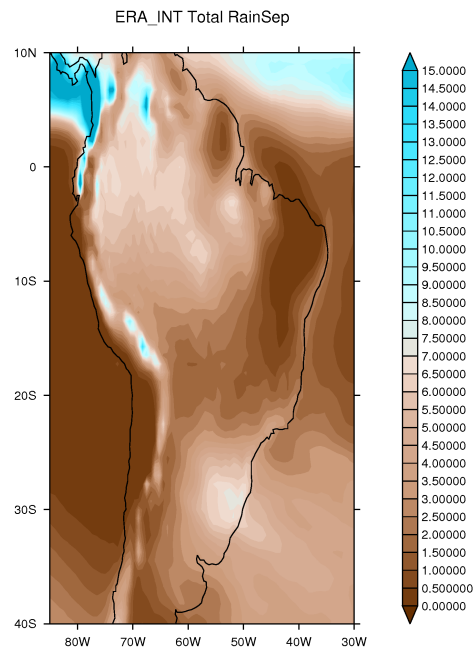
Figure 4. ERA-Interim September means over 1982-2012 for total precipitation.
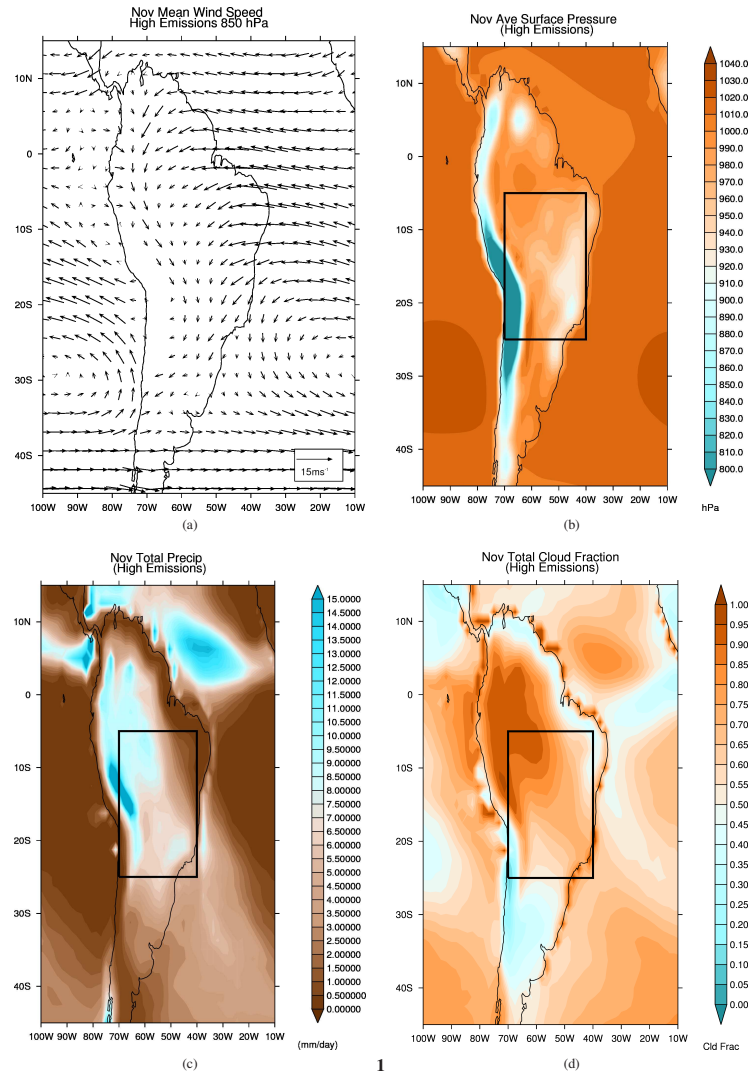
Figure 5. Mean monthly values for November high emissions case (a) Circulation at 850 hPa (b) Surface pressure (hPa) (c) Precipitation (mm/day) (d) Cloud cover