Response to Reviewer #2

We thank the anonymous reviewer for her/his thorough evaluation and constructive recommendations for improving this manuscript. Her/his comments (in italics) and our responses are listed below.

The study by Gonzalez-Alonso et al. explores the injection height of biomass burning emissions across the Amazon during the dry season and produces a climatology of smoke plumes heights derived satellite observations. Overall the paper is well written and concepts are described clearly (although some sections in the methods may benefit from a summary figure or table – see comments below). Figures are really nicely displayed and, mostly, very easy to understand. The topic of the study is well within the scope of ACP and I can see that this dataset will be very useful, particularly to modellers simulating processes & impacts of biomass burning in the Amazon region. I recommend publication once the comments below have been addressed.

We thank the reviewer for these kind words.

General Comments

1. The methodology explanation is very thorough and well written. However, the methods section is very long and sometimes a bit hard to follow, particularly for readers that are unfamiliar with these satellite products. I suggest adding a table or two (or extending Table 1) summarising the main datasets and tools used including information on the satellite products and the version used, resolution, overpass time etc. The methods section would also benefit from a schematic diagram perhaps just of the MINX software, to make the analysis process clearer.

As suggested by the reviewer, we have added a table summarizing the products and instruments used in our study. To avoid making the paper longer, we included this table in Supplementary Materials (Table S1) and added a reference in the text.

Page 3 lines 25-26

> "We provide below a summary of main datasets and tools used in the analysis and compile their main features in Table S1 (Supplementary Materials)."

We thank the suggestion about the MINX diagram, but we feel that there is already a significant amount of information in the literature about MISR smoke plume heights, e.g., Val Martin et al. (2010, 2018), Tosca et al. (2011), Mims et al. (2010), and the MINX software (Nelson et al., 2013), which we cite extensively throughout our manuscript, in particular Nelson et al. (2013). We prefer to refer the readers to these previous works.

2. In the paper, the authors make a good attempt to compare parts of the methods and results to previous studies. However, these sections are buried in the text. I wonder if it would make the manuscript clearer if you had a separate section where you compare the methods and results to previous studies? You could add a table including previous studies on plume heights in the Amazon either using similar or different methods (e.g. Baars et al., 2012; Marenco et al., 2016), summarising/comparing the findings of these studies and yours.

We thank the reviewer for this suggestion. We do compare different methods in the text and figures, as appropriate; however, we think that there are not that many studies on smoke plume heights over the Amazon to justify a separate section.

3. I agree with Referee #1, the results from CALIOP and MISR are so different that I believe the reader will be left feeling a bit unsure of what information to take from the paper (particularly atmospheric chemistry/aerosol modellers who may not be familiar with the details of these satellite products/tools). Can you make some recommendations in the conclusions?

We have reworded the manuscript to make clearer how results from MISR and CALIOP are complementary and, given differences in the sensitivity and sampling of these techniques, not so different.

In addition, as suggested by the reviewer later in Point 14, we extracted the PBL heights at the location and time of the CALIOP smoke plumes. As briefly mentioned in our manuscript, PBL is expected to grow further later in the day at the time of the CALIOP observation. We find that PBL at the time of the CALIOP daytime overpass (2-3 pm LT) is about 1.4 km deeper than at the MISR overpass time (10-11 am LT). A deeper PBL contributes to the difference observed between MISR and CALIOP smoke plumes. Fires can also become more energetic as the day wears on, increasing plume buoyancy and smoke injection height. This is an important point that we did not emphasize in our first version and we do it now. We made the following changes:

Page 14 line 33 - page 15, line 2

> […] In contrast, CALIOP observes smoke at higher altitudes during dry (2.2 and 3.4 km) than wet years (2.0 and 3.2 km). As discussed above, for the time and location of the MISR observations, a deeper PBL is observed in dry compared to wet years. Likewise, PBL heights at the CALIOP smoke plumes are 2.4 and 2.6 km in wet and dry years, respectively, and thus a deeper PBL during drought conditions explain the higher altitudes observed by CALIOP under drier conditions.

Page 15 lines 10-16

> In our study, CALIOP observes smoke at systematically higher altitudes than MISR, with median plume heights up to 1.4~km higher (2.2 km for the maximum plume heights). However, CALIOP still shows that the majority of the smoke is located at altitudes below 2.5 km above ground, consistent with previous observations from lidar measurements (Baars et al., 2012). Differences between MISR and CALIOP smoke plume heights are consistent with deeper PBL heights at the time of the CALIOP observation, as PBL is expected to grow further later in the day, and fires might also increase in intensity. We find that PBL height at the location/time of the CALIOP daytime smoke plumes is on an average about 1.4 km higher than for MISR smoke plumes, specifically 2.7 km for CALIOP and 1.3 km for MISR.

Conclusions, Page 16 line 7-9

> We find that CALIOP smoke plume heights are about 1.4-2.2 km higher than MISR smoke plumes, due to a deeper PBL later in the day, possibly more energetic afternoon fires, and CALIOP's greater sensitivity to very thin aerosol layers (Kahn et al., 2008; Flower and Kahn., 2017).

Abstract, page 1 lines 8-11

> A similar pattern is found later in the day (14:00-15:00 LT) with CALIOP, although at higher altitudes (2300 m grassland versus 2000 m tropical forest), as CALIOP typically detects smoke at higher altitudes due to its later overpass time, associated to deeper PBL, possibly more energetic fires, and greater sensitivity to thin aerosol layers.

4. I strongly suggest comparing your results to what is currently used/assumed in atmospheric aerosol/chemistry models for fire emissions injection heights. Do your results contradict or confirm what is currently used?

As suggested by the reviewer, we have added the requested information in the conclusions section.

Page 17 line 4-15

> A variety of smoke injection height schemes are used to represent fire emissions over the Amazon, from fire emissions injected below 3 km (Reddington et al., 2016) or into the model-defined PBL (Zhu et al., 2018) to complex plume rise models, in which a significant fraction of emissions are in some conditions injected above 6 km (Freitas et al., 2007). Recent efforts have shown the value of using MISR-derived smoke plume heights to initialise model fire emission injection (Vernon et al., 2018, Zhu et al., 2018). Over the Amazon, Zhu et al., (2018) show that a new injection scheme based on MISR plume-height observations, which included vertical smoke profiles used in this study (Val Martin et al., 2018), provide a better representation of CO observations over the region. With a very narrow swath but sensitivity to sub-visible aerosol, CALIOP tends to sample aerosol layers downwind, providing information complementary to the near-source mapping offered by MISR (Kahn et al., 2008). Thus, observations from both CALIOP and MISR provide a way to study smoke plume heights across the Amazon during the biomass burning season. Ultimately, this information will help improve the representation of biomass burning emissions in Earth system atmospheric models, and should aid our understanding of the feedbacks between droughts, terrestrial ecosystems and atmospheric composition over the region.

5. Following on from the previous general comments, for modellers it would be extremely useful to have idea of whole vertical distribution of the plumes rather than just median/max plume height. For example, the average percentage of the plume in specified altitude bands. Could this information be estimated from the CALIOP data? Or perhaps this would be unreliable given the large difference between CALIOP and MISR results?

CALIOP data are not sampled well enough to make the reviewer's suggestion viable. In addition, differences in actual sensitivity between MISR and CALIOP present an additional limitation. The analysis suggested by the reviewer has recently been published in Val Martin et al., (2018). In that work, the Authors present a statistical summary of vertical distribution of smoke (%) by land cover, region and season, from 0 to 8 km at 250 m bins based on MISR stereo-derived smoke plume heights. These profiles are snapshots at the time of the MISR observations (10-11 am LT), but they provide a constraint to initialise fire emission injection heights in climate and atmospheric chemical transport models. Zhu et al., (2018) present an example where this MISR-based injection height scheme is implemented and evaluated within GEOS-Chem, a major atmospheric chemical transport model. As discussed in point 4 above, we added a reference to Val Martin et al (2018) and Zhu et al (2018) in our manuscript.

Specific comments

1. Abstract, L2: Specify the dry season months

Added as suggested. Note that this is also the primary burning season.

2. Abstract, L4-6: Sentence not written very clearly "About 60% of smoke plumes are observed during drought years, at the peak month of the burning season (September; 40–50%) and over tropical forest and savanna regions (94%)." Does this mean: 60% of smoke plumes were observed in drought years (relative to non-drought years); 40-50% observed in the peak month of burning season (relative to the other months); and 94% observed over tropical and savannah regions (with the remainder over grassland)?

We have reworded the Abstract to make these results clearer.

Page 1 lines 4-6

> About 60 % of smoke plumes are observed in drought years, 40-50 % at the peak month of the burning season (September) and 94 % over tropical forest and savanna regions, with respect to the total number of smoke plume observations.

3. Introduction: Order citations correctly (by year).

Ordered as suggested.

4. Introduction, P2, L12-14: Can you include any references for why altitude to which smoke is injected is critical? Perhaps give examples of modelling studies where this has been tested e.g. some of the SAMBBA modelling papers, or observational studies.

Added references as suggested. Specifically, Jian and Fu, 2014, Archer-Nicholls et al., 2015, Paugam et al., 2016, Zhu et al., 2018.

We have also included information about the SAMMBA modelling studies as follows.

Page 3, lines 6-8

> […] For example, modelling studies during SAMBBA showed the importance of the vertical representation of aerosols from biomass burning over the region (Archer et al., 2015), as biomass burning can modify local weather (Kolusu et al., 2015) and regional climate (Thornhill et al., 2017).

5. Introduction, P3, L1-3: The Kolusu et al. (2015) and Thornhill et al. (2017) papers are modelling studies not observational (correct this sentence).

Corrected, as suggested.

6. Introduction, P3, L9-10: ". . .no analyses yet that seek to quantify the vertical distribution of smoke from fires across the Amazon. . ." Suggest changing to: ". . .quantify the long-term average vertical distribution".

Changed as suggested.

7. Sect. 2.1: How are the MISR and MINX vertical resolutions accounted for? Apologies if this explained later in the manuscript.

The MINX vertical resolution is between 250 and 500 m, depending on observing conditions, and we take it into consideration throughout the study. This is mentioned in page 4 lines 15 and 23.

8. Sect. 2.6: Why was 0.5x0.5 degrees resolution chosen for CALIOP?

We ended up having a massive dataset when we compiled raw CALIOP aerosol extinction observations (night and daytime) over the Amazon for 5 months and 7 years. This raw dataset required a long processing time to re-grid them into smoke plumes. So, we first ran a test for one month at 0.1x0.1 and 0.5x0.5 horizontal resolution and decided to process the 7-year observations at 0.5x0.5 as the data were easier and quicker to process and we did not introduce any bias because of the chosen resolution. We clarified this in the manuscript.

Page 7 lines 14-17

> We first grid all CALIOP aerosol extinction profiles classified as smoke (day and night) at a horizontal resolution of 0.5°x0.5° over the Amazon region, and a vertical resolution of 250 m, from the surface to 12 km. We chose this horizontal resolution to optimise computing processing time. […]

Page 7 lines 22-25

> To ensure we do not introduce a bias in the CALIOP plume heights due to the 0.5x0.5 horizontal resolution, we also retrieved the smoke plumes for the 2017 burning season at a horizontal resolution of 0.1x0.1, and find no significant differences. For this subset, our 0.5x0.5 method returns 131 plumes, with an average altitude of 3.65 km for the maximum plume heights, whereas the 0.1x0.1 method returns 149 plumes, with an average altitude of 3.74 km.

9. Sect. 2.6 (P7, L26-35 – P8, L1-5): Nice explanation of the other CALIOP products that have been used by previous studies. This may be helped by a table summarising: the studies (including yours), different products used, region studied etc. Also, is it possible to briefly say what the implications are for using these different products and explain why the specific product and plume height definition were chosen for your study over the others?

We thank the reviewer again for this suggestion. As mentioned above, we feel that the number of studies over the Amazon is not large enough to justify a table, and our manuscript already contains a large number of tables and figures.

We have reworded section 2.6 to accommodate one comment from reviewer 1 regarding the MISR and CALIOP comparison and why we chose a new approach to derive the smoke plume heights from CALIOP. We hope the new wording/discussion makes this point clearer, and addresses this comment as well.

10. This sentence from Sect. 3.1: "The majority of the plumes in this record are digitised with blue band retrievals (Table 1). . .", seems to contradict the following two from Sect. 2.2 (or at least have confused me): "This screening leaves a total of 5393 plumes, about 56% of the original database, with 77% and 23% plumes digitised in the red and blue bands, respectively.", and "In our dataset overall, most of plumes are digitised with red band images, as it was the default option for MINX v2–3."

We refer as "the majority of the plumes in this record" as plumes in 2008, not to the whole dataset as in Section 2.2. We clarified this point in Section 3.1.

11. Be consistent with use of "PBL"/ "BL".

Corrected as suggested.

12. P12, L7 & L17: What are the p-values and at what confidence level is the relationship statistically significant?

Added as suggested.

13. P13, L15-16: "Our results suggest that fires during drought periods might significantly degrade regional air quality, as they are associated with low smoke altitude and large aerosol loading.". The finding that drought periods are associated with large aerosol loadings, which substantially degrade regional air quality is consistent with Reddington et al. (2015) (and other studies?). The higher aerosol loadings are likely due to the increases in the number/size of fires (e.g. Aragão et al., 2007; 2014) and subsequent increases in aerosol emissions. However, the potential for lower smoke altitudes in drought years, I'm assuming, is a new finding and should be highlighted/made clearer.

We thank the reviewer for this comment. We have reworded the manuscript to strengthen this new finding as follows:

Page 13 lines 30-32

> Years with drier conditions have almost a factor of three greater AOD compared with years with wet conditions. Larger aerosol loading in drought periods is likely due to increases in the number and size of fires (e.g., Aragao et al., 2014) and subsequent increases in aerosol emissions.

Abstract lines 18-22

> Consistent with previous studies, the MISR mid-visible aerosol optical depth demonstrates that smoke makes a significant contribution to the total aerosol loading over the Amazon, which in combination with lower injection heights in drought periods, have important implications for air quality. This work highlights the importance of biome type, fire properties and atmospheric and drought conditions for plume dynamics and smoke loading.

14. P14, L18-19: Would it not be possible to check the PBL height around CALIOP overpass time with MERRA2 data?

We thank the reviewer for this suggestion. We had already analysed the PBL height at the time of the CALIOP overpass time, but did not include this analysis or show any of the results in the original version. We reworded the manuscript to make this result clearer as discussed in point 3 above.

15. I'm not sure I understand how Figure 8 demonstrates the following statements: - P12, L7-9: "We find a significant positive relationship between MISR maximum plume heights and MODIS DSI (r=0.7) in tropical forest and savanna fires, with higher maximum plume heights in wet (1000–1100 m) than severe drought conditions (800–900 m) (Figure 8)." - P13, L3-4: ". . .tropical forest fires inject a larger percentage of smoke plumes into the FT in wet than extreme-dry conditions (12 versus 20%, Figure 8)". Since I can only see data points for tropical forest in "Extreme- Severe" and "Mild Moderate" conditions, with one point in "Normal" and none in "Wetter than Normal".

We have reworded the text to make our results clearer.

Page 12 Lines 23-25

> We find a significant positive relationship between MISR maximum plume heights and MODIS DSI ($r=0.7$; $p<0.01$) in tropical forest and savanna fires, with higher maximum plume heights in normal and/or wetter than normal (1000-1100 m) than severe drought conditions (750-900 m) (Figure 8).

Page 13 lines 25-27

> Note that in Figure 8 (right bottom), we present the data only subdivided by MODIS DSI and biome, regardless of the year, as in the rest of the panels in Figure 8.

Tables & Figures

1. Table 1: suggest adding a "total" row in the table.

Added as suggested.

2. I suggest adding a table to summarise smoke plume heights for the main biomes (could also add drought/non-drought year averages) to compliment Figure 10. So that readers can get this info quicker than reading it off a figure.

We have most of this information in Table S2 (former Table S1).

3. Figure 2: I suggest adding one or two figures (perhaps to supplementary) to show the month and/or year the plume occurred e.g. with different colours.

We thank the reviewer for this suggestion. Showing the smoke plumes per year and month was originally in our plan. However, we tried to recreate the figure using different shapes and colours per month and year but it was hard to make a clear map to show the different locations due to the amount of data points in the 8-year climatology. We decided to present only the main figure with all smoke plume locations in black. In most respects, this information can be gleaned from the plots in Supplemental Material.

4. Figure 10: If the differences between Day and Night CALIOP Median Plumes are not significant then is it worth just combining these here (keeping the separation in the previous figure)? It is really the difference between the CALIOP and MISR estimations of plume heights that is the significant result.

We thank the reviewer for this suggestion. We have modified the figure and reworded the manuscript accordingly.

Page 14 Lines 23-28

> Figure 10 summarises the median and maximum heights for the CALIOP smoke plumes per biome, season and wet/dry years. Night-time plume heights are on average 250 m higher than daytime plume heights (Figure 9). Differences between day and night-time CALIOP observations have been attributed in the past to a low bias in the daytime retrievals due to noise from scattered solar radiation (e.g., Winker et al., 2009, Huang et al., 2015). Therefore, our difference in day and night-time CALIOP plume heights might result from differences in data quality rather

than reflecting smoke diurnal variability. We combine day and night-time CALIOP observations in Figure 10 and include the MISR plume heights for comparison.