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Interactive comment on "Theoretical uncertainties for global satellite-derived burned area estimates" *by* James Brennan et al.

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AC: We thank the reviewer for their useful comments on the MS. Below we address their concerns and provide revisions to the MS.

Reply to general Comments

RC1: The study provides uncertainty estimates for satellite burned area datasets. The methods are plausible and certainly go beyond any approach that has been described before. The manuscript is well written and requires only in few places some clarifications. Understanding uncertainties in datasets is crucial to apply them and to extract information that is valid. The manuscript does however provide only few background on how these uncertainty estimates can be used.

AC: We thank the reviewer for these kind comments. We agree that the discussion on how these uncertainty estimates can be used is too limited. To address this we have added a paragraph to the discussion proposing ways in which the uncertainties can be used by users: "While the TC-estimated uncertainties can not directly provide information on uncertainties at the pixel level, we would also encourage users to consider the quality assurance (QA) information provided in these products. The presented TC uncertainties have many uses. The uncertainties could, for example, be used to drive development and refinement 35 of parameters in dynamic vegetation models related to fire processes or improve optimisation routines for parameter selection (Poulter et al., 2015; Forkel et al., 2019). They could also be used to better constrain uncertainties on emission estimates derived from 'bottom-up' inventory approaches (Randerson et al., 2012; French et al., 2004; Knorr et al., 2012; Van Der Werf et al., 2017). Explicit uncertainties additionally allow for the development of more advanced assimilation of the satellite observations into models through mathematical frameworks in data assimilation."

RC1: The method also only represents random errors. This is a big limitation as the true burned area is likely far higher than what is estimated with these coarse resolution datasets. A recent study using Landsat data estimates an 80% higher burned area for Africa (Roteta et al. 2019). This indicates that the systematic errors are high and global burned area estimates of all globally available datasets are likely far too low. However, the relative differences of uncertainties between regions and between land cover types may be very useful in spite of the lack of including systematic errors in the uncertainty estimates. Including the recent publication (Roteta et al. 2019) in the discussion and the consequences for the interpretation of the uncertainties presented here is necessary. A broader discussion of how such uncertainties can be used in modelling studies and data analysis could strongly increase the impact of the paper.

AC: We agree that the ability of the TC method to only account for random errors is a limitation of the method. Systematic errors originating primarily from missing small fires in the coarse resolution products will ultimately inflate the total uncertainty in the

products. We would therefore regard the estimated uncertainties as providing a lower bound on the total uncertainty, in the absence of systematic errors (with the view that Total uncertainty=systematic + random errors). Given this, we agree with the view that the relative differences between regions and land cover types may actually be more useful for some users and still represents the most granular estimate of uncertainties available for these products.

We have included an additional section about this into the considerations of the TC method (section 5). "We also stress that the uncertainties estimated with the TC method likely represent a lower bound on the true uncertainties of these products. The TC measurement model can only explicit estimate random errors but not the likely systematic errors (i.e. bias) present in the data products. The under-estimation bias observed for these coarse-resolution products in validation studies indicates that the products likely have considerable systematic errors. Chuvieco et al. (2018) have estimated that the FireCCI50 product has global omission errors of 70% and MCD64C6 62%, which are partially balanced by commission errors of 50% and 35% respectively. Roteta et al. (2019) also indicated that a higher spatial resolution 20m burned area product provided 80% more burned area than the MCD64C6 product for sub-Saharan Africa, indicating considerable biases in coarse-resolution products. Users should be aware therefore that the likely systematic biases in coarse resolution products mean that the TC uncertainties provide a lower bound on the true uncertainty."

Reply to specific comments

RC1: p.1, l. 1/2: essential for the scientific application of these datasets.. They are already used in science so please be more specific on why uncertainties are important.
AC: We have clarified this in the abstract to reinforce that the uncertainties are "essential for evaluating the quality of these products and comparison against modelled estimates of burned area".

RC1: p.1,l. 9: how about data analysis studies?
AC: We have added reference to data analysis studies.

RC1: p.1,l. 5-6: how are these uncertainty measures to be interpreted given new data products that indicate 80% higher burned area in Africa?
AC: We think this is addressed by the discussion about systematic errors above.

RC1: p.1,l. 12: looks like a unit (m-1 km) probably change to 250-1000m, or anything else more precise.
AC: This is changed to (250m-1000m).

RC1: p. 4 l. 3: total burned area of what? the gridcell? The method also assumes that the error scales with the magnitude of the burned area, which is mentioned on p. 5 (heteroscedasticity). Here some restructuring would be useful.
AC: We have clarified this as: "the aggregated burned area in the grid cell".

RC1: p.4 l. 5 : Another arising concern is that the standard error maybe not only scales with the magnitude of burned area but other factors could be important. For instance land cover (e.g. woody cover that could hide subcanopy fires, cropland cover that usually is exposed to small sized fires, cloud cover, or other failures of the sensor or data transmission).
AC: We think this is a good point and a potential limitation of that method. We've addressed this by adding an additional paragraph: "An additional limitation of the regional enumeration of c_B is that it must replicate contributions from additional uncertainty sources. These will be features such as variations in cloud cover obscuring burned area detection, and uncertainties arising from variations in the distribution and local mixture of vegetation type. This variability will alter the value of c_B within each region."

RC1: p.4 l. 7: how large are they, how do they differ from GFED
AC: this has been clarified with reference to the 103 validation tiles used in that paper.

RC1: p.4 l. 21: Rabin et al. 2017: is this the correct ref? This is a model documentation paper
AC: yes, Rabin et al. 2017 refer to: "There are multiple datasets available for some of these properties, including, for example, burned area. Padilla et al. (2015) have

shown that currently available burned area products differ considerably both in terms of global total and at a regional scale. Differences between datasets effectively define the current range of uncertainty in observations, and this level of uncertainty needs to be taken into account when evaluating model performance." Page (1190)

RC1: p.4 l. 21-22: I don't understand what you want to say here?
AC: Thanks, we have rephrased this section to (hopefully) improve clarity.

RC1: p.4 l. 23: how are these uncertainties estimated?
AC: Le Page et al. (2015) detail that these are provided based on considering the papers for GFED/MCD45 and also comparing versions of GFED (pg. 895). We added "based on an inspection of the GFED data" to the manuscript.

RC1: p.5 l. 20: What is the distribution of the errors?
AC: these are considered here to be normally distributed. We have added "are considered to be normally distributed".

RC1: p.5 l. 25: the random errors or the standard deviation of the random errors is correlated with the magnitude?
AC: The standard deviation of the random errors. The random error model is formulated as normal distribution such that the errors are drawn from $N(0, \sigma)$. The multiplicative model deals with the characteristic that $\sigma = f(BA)$. We have clarified this in the manuscript.

RC1: p.5 l.26: Figure 1 could be changed to show the standard deviation over the products vs. the mean. That would more clearly show the heteroscedasticity and also the homoscedasticity for the log transformed data.
AC: Thanks, this is a good suggestion for figure 1. We have changed figure 1 to now plot mean over the products (x) vs individual product (y) and also the standard deviation of the products scaling with x. This makes the heteroscedasticity/homoscedasticity of the transform more apparent.

RC1: p.6,l. 12,p.7 l.1: move the "C" to directly follow "sample covariance matrix"
AC: Thanks, done.

RC1: p.7 l. 11-15: how about using the square root or maybe 10th root transformation to keep the 0 values?
AC: We thank the reviewer for this suggestion. Various transforms were also considered but an unfortunate feature of transforms other than the log transformation is the complication of the triple collocation model. The multiplicative model as phrased works because the log-transformation provides a multiplicative error which is linear in log-space. Further transforming a square-root transformed linear triple collocation such as $\sqrt{x} = \alpha + \beta\sqrt{T} + \epsilon$ back into real units (km^2) does not equate to a model in which the error ϵ fulfils the properties of being multiplicative, or indeed a random error component.

RC1: p.7 l.1: Why are the annualised uncertainties of interest? please provide an overview on how uncertainties can be used and how the uncertainties are used by users at some place in the manuscript (maybe introduction).
AC: We found that annualised estimates provided an efficient method to summarise regional disparities most clearly in a visual manner (e.g. figure 7). The actual uncertainties are provided for each 16-day period in the observational record (2001-2013) of the products, which is being registered with an online data repository. Annual burned area is also generally the focus of previous inter-comparison studies such as Humber et al. (2018) and also the papers describing the products e.g. Giglio et al. (2018). We agree that more information should be provided on how these uncertainties could be used and have added a section on this to the discussion detailed earlier. We have also extended the brief section on user requirements for uncertainties in the introduction (Pg2, L11).

RC1: p.8. l. 5: what about temporal auto-correlation of errors?
AC: we agree with the reviewer that an understanding of the auto-correlation of the uncertainties would be useful. However it is not easy to estimate this auto-correlation without a full treatment of the uncertainties in burned area at the pixel scale (i.e. in-

cluding the temporal uncertainty which is only available for MCD64) and how this could be properly aggregated to the grid-scale burned area. Unfortunately the triple colloca-tion method as formulated is not able to formulate auto-correlation of errors but also assumes no correlation in errors between products.

RC1: p.8 l. 12: total burned area of individual years or a multiyear mean?
AC: thanks we have now clarified this by adding "for each individual year".

RC1: p.8 l. 14: reason for using land cover type classification is that you assume that the local fire behaviour is driven by land cover type? Please clarify and add a reference for this assumption.
AC: This is a good point and variations associated more with fire characteristics (or fire pyromes) may be better. We chose to focus on the combination of the GFED regions and broad land cover classes because this formulation has been used previously for several papers and would hopefully be familiar to readers. Some examples are Giglio et al. 2010, 2013 for GFED which uses the regions and these land cover super classes. The papers describing MCD64 also use this formulation (Giglio et al. 2018) and the paper for FireCCI MERIS (Alonso-Canas et al. 2015).

RC1: p.9 l. 2: change to "4) savannas"
AC: changed.

RC1: p.9 l. 13-14: maybe add that no assumptions on the error structure are necessary in that way.
AC: thanks. We have added "while requiring no additional assumptions about the error structure".

RC1: p.9 l.18-19: what does it actually mean if the random errors are larger than 100%? can the data be used for anything at all? Or is there no information content in these parts then?
AC: This would indicate yes that in these locations the precision of the burned area is actually less than the uncertainty. This most obviously arises when the three products

provide very divergent estimates such that the products show little agreement on the magnitude of burning. In such cases the products should be trusted least. To pro-vide more information on this we have added: "This would indicate that the level of agreement between the products is lower than the precision of the products".

RC1: p.9 l. 33: As far as I know the FireCCI50 dataset has only been released last year, are you sure it is included in Humber et al. 2018? In their description it says the product is based on MERIS.
AC: Yes this is a mistake – Humber et al. 2018 analyse FireCCI MERIS. We corrected this by referring only to MCD64 in reference to Humber et al. 2018.

RC1: p.10 l. 4: what exactly is consistent?
AC: consistency here means that the distributions of burned area for each product show overlap – i.e. the products agree within their uncertainties. We have clarified this as "consistent within the uncertainties".

RC1: p.10 l.6-7: maybe a root transformation could be advantageous then.
AC: See the comment above about the problems of a root transformation for the triple collocation error model.

RC1: p.11 l. 9: mean annual burned area?
AC: Thanks, corrected.

RC1: p.12 l. 1: why are the uncertainties in shrublands high? has this been docu-mented before? the higher uncertainty in croplands is well known due to the smaller fire size. But what could be a reason for high uncertainty in shrublands?
AC: We also found this an interesting finding that (as far as we are aware) has not been documented before. Our primary view is the likely difficulty of detection here from 500m data arising from burn 'patchiness' as a response of the limited and discontin-uous fuel bed in shrublands. The much lower vegetation density in shrublands will limit the magnitude of the radiometric burn signal pre-to-post fire – limiting the change signal the algorithms use to classify burning. Combing the limited vegetation signal

with the general sparseness of vegetation ground cover in shrublands will lead to this 'patchiness' of the burn signal which when observed at 500m will likely fall around the detection thresholds of these burned area mapping algorithms (for example see Roy Landmann, 2005). The aggregated uncertainties for shrublands also hides the fact that the uncertainties for 'hot' (xeric) and 'cold' (tundra etc.) shrublands varies quite considerably. The large relative uncertainty for MCD45 recorded in Australia (primarily xeric) shrublands is potentially a feature of the limited performance of the algorithm over surfaces with bright soils (Roy et al., 2005; de Klerk et al., 2012). This is not replicated for 'cold' shrublands the same manner which generally have darker soils. We have added this to the discussion of the paper:

"The large relative uncertainties in shrubland burning have not been previously highlighted for global satellite burned area products. A potential mechanism for this is a detection threshold associated with the limited and discontinuous fuel bed in shrublands. The limited vegetation density in shrublands will limit the magnitude of the radiometric burn signal pre-to-post fire – limiting the change signal the algorithms use to classify burning. Combing the limited vegetation signal with the general sparseness of vegetation 30 ground cover in shrublands will lead to this 'patchiness' of the burn signal which when observed at 500m will fall around the detection thresholds of the mapping algorithms considered here (Roy and Landmann, 2005). The large relative uncertainty for MCD45 recorded in Australian (primarily xeric) shrublands is potentially a feature of the limited performance of the algorithm over surfaces with bright soils (de Klerk et al., 2012; Roy et al., 2005). This is an interesting that represents a promising area for future research."

RC1: p.12 l.8: 8-10% seems low, given that the contribution of small fires, which are suggested to be mostly cropland fires is around 100 Mha (Randerson et al. 2012). And what does this estimation of the random error mean for the global extent of cropland burning? Systematic errors are not considered and the main effect of the small sized fires should be a systematic underestimation of the burned area on croplands.

AC: We agree that croplands will have higher systematic errors due to omission errors

for some products. We would argue that it is difficult to be sure about the likely direction of this effect however due to observed commission errors by MCD64 for harvesting in Eurasia and MCD45 in Australia (Humber et al. 2018). Because of these discrepancies in the response of products we could realistically expect that at least some of the systematic error is present in the random errors of the products. To comment on this we have added to the text: "However, discrepancies between the products are likely to still be driving the TC uncertainties, for example" observed commission errors by MCD64 for harvesting in Eurasia and MCD45 in Australia (Humber et al., 2018; Giglio et al., 2009)"

RC1: p.12 l. 13-15: First sentence says lower uncertainties in BOAS, second sentence says larger uncertainties in BOAS. Please clarify.

AC: Thanks, this is clarified as: "Uncertainties for MCD45 are around two times larger in BONABOAS forests, and 40% larger for FireCCI50 in BOAS as compared to BONA forests. Alternatively, MCD64 has lower relative uncertainties in BONA compared to BOAS, with uncertainties 70% larger in boreal Eurasia."

RC1: p.13, l. 3: what is the shared uncertainty envelope and where can it be seen?

AC: This refers to the central BA estimates being within the standard errors of each product. Such that the distributions of each product overlap within 1 standard deviation. We have clarified this in text by substituting the "uncertainty envelope" for "for each product agreeing within the uncertainties estimated for all products".

RC1: p.13 l. 4: now the relative uncertainties for savannas are larger than for croplands?

AC: For northern Hemisphere (NHAF) and southern hemisphere Africa (SHAF) relative uncertainties in savannas are larger than croplands. To make this clearer we have rephrased this to: "The uncertainties are still considerable, however, with relative uncertainties for all three products largest in savannas and grasslands. In these land covers, relative uncertainties exceed 13% in NHAF and 8% in SHAF."

RC1: p.13 l. 7: "region" is double.
AC: Thanks.

RC1: p.17 l. 3: " as evidenced..." I do not understand, can you explain this better?
AC: this refers to the discontinuous patterns that can be seen in the probability field for FireCCI50. These most likely occur due to the compositing method used in the algorithm which determines the number of available observations for the retrieval of burned area. The same tesselation pattern can be seen in the ATDB for the algorithm on page 29. (https://www.esa-fire-cci.org/sites/default/files/Fire_cci_D2.1.3_ATBD-MODIS_v1.1.pdf We have clarified this in the manuscript by: "with the apparent pattern in unburned confidence values arising from the interpretation of the composited observations used within the algorithm."

RC1: p.18 l.12-13: do you mean errors of your error estimates or the estimated errors?
AC: This section refers to potential sources of correlations (ECCs) in the actual errors between products and the true burned area. Depending on the strength of these EECs, the assumptions of the triple collocation method may not be met. So this section explores whether the uncertainty estimates are likely to be "tainted" by ECCs. We've clarified that ECCs alter the quality of TC uncertainties in this paragraph.

RC1: p.19 l. 11: but the uncertainties for shrublands were largest?
AC: This is correct – shrublands did have larger relative uncertainties globally for all three products than croplands. To clarify this we have rephrased the first sentence to: "A feature of the TC analysis shown here is the large relative uncertainties across croplands and shrublands globally". We have then also added a discussion about the potential mechanisms for large shrubland uncertainties as detailed above.

RC1: p. 20 l. 1: globally there should be still a large underestimation due to the coarse resolution. for instance Roteta et al. (2019) recently estimated a 80% higher burned area in Africa. How does this influence the interpretation of the here presented uncertainties. The true global burned area is then very likely outside of the range of global

burned areas presented here, as only random errors are captured.
AC: We partially agree with the reviewer here. The underestimation by coarse resolution products detailed in Roteta et al. (2019) will ultimately mean that the true uncertainty on the coarse resolution products will be larger. This systematic error which we referred to earlier may exceed the random error for some regions. Because of this users should be aware that these uncertainty estimates represent a lower bound on the true uncertainty. We would also caution that while for some regions the systematic error > random error this may not be the case for all regions It has not been established how large the global underestimation will be with the additional consideration that a portion of every 500m pixel labelled burned in the products will only be fractionally burned. To address this point we added the section detailed above to Section 5 on systematic and random errors.

RC1: p.20 l. 7: I can't find confidence bounds presented in Rabin et al. 2017.
AC: Rabin et al. (2017, pg. 1190) refer to the "Differences between datasets effectively define the current range of uncertainty in observations, and this level of uncertainty needs to be taken into account when evaluating model performance."

RC1: p.21: I think the conclusions as well as the discussion chapter should provide information how and for what the uncertainties can be used. You write theoretical uncertainties, but they are meant to be used in practice right?
AC: We agree with the reviewer here. To address this we have added the paragraph detailed earlier to the discussion.

RC1: p.21 l. 11: what do you mean with unique error characteristics? the regional and land cover specific differences in uncertainties?
AC: Thanks, exactly that. To improve this we have added "and the regional and land cover specific differences in product confidence as provided by these uncertainties."