Interactive comment on "Modelling fires in the terrestrial carbon balance by incorporating SPITFIRE into the global vegetation model ORCHIDEE – Part 1: Simulating historical global burned area and fire regime" by C. Yue et al.

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As Referee #1 remarked, in reading this discussion paper we (Mirjam Pfeiffer, Allan Spessa, Jed O. Kaplan) were surprised that our paper and the technical revisions we made to the SPITFIRE model appear to have not been taken into account in the current model description. We realize that much of the development of ORCHIDEE-SPITFIRE may have occurred in parallel with our own work, but our discussion paper was published in August, 2012, and the final version of the paper was published more than a year ago, in May, 2013. In our paper, we highlighted several important limitations in the original SPITFIRE implementation, and provided solutions for overcoming these, and included a complete listing of all of the original and new equations we used. Furthermore the LPJ-LMfire source code is, following GMD publishing guidelines, publicly available here: http://sourceforge.net/projects/lpjlmfire.

The authors of the current manuscript argue that their model is a step in the direction of understanding wildfire at global scale. Given recent progress made in global fire modeling, we disagree, and believe that the current manuscript has missed an opportunity to make real progress in improving our understanding by building on previous research work, including ours. Specifically, the last two paragraphs of the discussion section of the current manuscript should be focused to more clearly describe the most important priorities for improving global fire models in light of not only the authors' own interpretations of the limitations of their model, but also other recent developments in global fire modeling, including ours. Aside from crown fire, Pfeiffer et al. (2013) provide solutions for modeling all of the points highlighted for improvement in the last paragraph of the discussion section (Pg 2405, lines 17-19).

[General response] We thank Jed O. Kaplan, Mirjam Pfeiffer, and Allan Spessa for the great interest in our study and thoughtful comments on our work. As our development was somewhat in parallel with theirs (although our submission was delayed), it was rather difficult to include their developments directly into our model, given the tight time schedule, and the large amount of work in code integration, test simulations and analysis in integrating a separate fire module into a complex model like ORCHIDEE. Besides, as ORCHIDEE and LPJ are two different models, it's difficult to expect these new developments will work directly in ORCHIDEE as they do in LPJ. However, we acknowledge that the developments in Pfeiffer et al. (2013) represent a significant amount of work and should definitely be cited and discussed in our study, which is now included in many sections of the revised manuscript.

We developed an approach to group the daily fires into "multi-day fire patches" and argue that, though not exactly the same, this approach works in somewhat similar way as the "multi-day burning" scheme in Peiffer et al. (2013) and allows the simulated fire size being able to be compared with observation. Due to the difference in handling lighting ignitions in Pfeiffer et al.

(2013) and our model, we did not include the "coalescence" of fires in our model. Please refer to our response to #1 reviewer comments (Page 3) for more details. We have also tested the possibility to include the interannual lightning variability in our model, please refer to the response below and the "Response supplement material". All these changes and discussions are included in the revised manuscript.

The major aims of our manuscript are to document the integration of SPTIFIRE into ORCHIDEE, calibrate the model performance, and to conduct a review of error sources of the model when the observation data is available, especially by comparing the simulated fire size and fire numbers against observation. We hope to reveal more details in the model error by checking on at each key modelling step, to understand why and how the good simulation, overestimation or underestimation occurs. Because we believe this careful examination of modelling chain is needed for mechanistic simulation of fires and we think this is where the previous studies put not enough focus. Please see our responses to the individual comments in detail as below.

We would like to reiterate the importance of commenting on the following specific points in any revision of this manuscript:

• We found that representation of fires that persist over consecutive days was critical to making realistic simulation of fires in boreal regions, where ignitions are rare and fires can grow to very large sizes. Not representing multi-day burning in ORCHIDEE may be one of the important reasons why fire size is underestimated in the ORCHIDEE simulations.

[Response] We developed an approach to group the daily fires within consecutive days into "multi-day fire patches" to make the simulated fire patch size being able to be compared with observation. Though exactly not the same, we think this approach functions somewhat similarly as the "multi-day burning" scheme in Pfeiffer et al. (2013), given the fact that daily fire size is limited by the 241-minute fire active burning time (duration time) in both models. Please also refer to our response to the #1 reviewer comments (Page 2). This change is included in the revised manuscript section 2.5.2, and discussed in section 2.4.2 and 2.4.3.

• The rationale for ignoring agricultural burning in ORCHIDEE is not well argued for. For example, we suggested that anthropogenic burning was the main cause of fires in the miombo woodland region of Southern Africa, in South Sudan and the Central African Republic, and in southern Russia and Kazakhstan. If, as noted by Referee #1, the Randerson et al. (2012) burned area dataset is used instead of GFED, the modeled burned area is even more underestimated compared to observations.

[Response] We included the anthropogenic burning on all the land cover types except the cropland, according to GFED3.1 data, burned area on cropland is 16 Mha yr^{-1} for 1997-2009, or 4% of the global burned area. If the Randerson et al. (2012) data is included, the cropland burned area will be higher and the global total burned area will be higher as well. So far the publically available GFED4 data does not include the "small fires" (http://www.globalfiredata.org/data.html) and the GFED3.1 was the best available when we prepared the manuscript.

Of the other modelling studies based on SPITFIRE after Thonicke et al. (2010), the anthropogenic ignitions were not included in LPX by Prentice et al. (2010). Pfeiffer et al. (2013) developed complex schemes for human ignitions for the pre-industrial time but the anthropogenic ignitions were not included in their comparison with observation data. Lasslop et al., (2014) used some scalar to adjust the human ignition parameter in order to match the simulated global burned area with the observation. Thus we argue the ignition uncertainties tend to be challenging for all models, and matching the model with the observation needs always to be re-adjusted according to the update in the observation data. And this is also the case for us when the "small" fires are finally confirmed by the mainstream observation community and included in most observation datasets.

We did not include the crop fires, because crop fire simulation is highly dependent on a good crop phenology module, which is now under active development. Besides, fire spread and fire size in crop fires are completely limited by human activities and cropland size (which might depend on different agricultural practices in different countries), which is fundamentally different from wildland fires. All these features of crop fires warrant a special module to handle them and will be included in our future model development. However, the anthropogenic burning for the agricultural purpose that occurs in the woodland regions of Southern Africa (slash & burn, as suggested by, for example Scholes et al. 2011) is included in our model.

• We agree with Referee #1 that, if the authors insist on using a(ND) as a scaling factor for anthropogenic ignitions, it should be spatially variable instead of a global constant. The perfectly constant offset in global burned area between spatially variable and constant a(ND) – the black line and gray lines presented in Fig. 6 – looks suspicious to us. If the interannual variability in burned area is caused by climate variability, it seems to us that the offset should not be constant over time as different parts of the world have ideal fire weather in different years. In any case, some more comment on the utility of a(ND) would be useful.

[Response] The spatial a(ND) dataset is used in the revised manuscript. The offset between the two simulations with the universal a(ND) value and the spatial dataset has little interannual variation, probably because the dynamic vegetation module is switched off and the feedback between vegetation distribution and fires is limited.

• We explain in Pfeiffer et al. (2013) that fire rate of spread was strongly influenced by surface fuel accumulation and fine fuel bulk density. As noted by Referee #1, the 95th quantile fire rates of spread simulated by ORCHIDEE are excessively high in some places, particularly in the northern boreal forest and tundra regions. With an implementation of multi-day burning as in LPJ-LMfire, these very high rates of spread lead to unrealistically large burned area. We solved this problem by making the bulk density of fine fuels more realistic by implementing a compacted surface litter pool (O-horizon) in LPJ-LMfire, and by making the bulk density of the C3 grass PFT – this is the main plant type that occurs in tundra regions – a function of climate.

[Response] The spatial extent of slight overestimation by the model for the region north of 50^{o}N might visually look large (Figure 4 of the discussion paper), in fact they're of very low annual burned fraction (0.1~0.5%), and Figure 5 of the discussion paper shows that for the region of 50~75^{o}N the model simulation agrees with GFED3.1 data relatively well (10.5 Mha yr^{-1} by GFED3.1 vs. 11.2 Mha yr^{-1} by ORCHIDEE for the region of 50~75^{o}N). Thus overall total amount of burned area for the region north of 50^{o}N is not (significantly) overestimated by the model.

The significant overestimation by the model compared with GFED3.1 data in the northern hemisphere mainly occurs for the region of 30-50°N (see Figure 4 and Figure 5 of the discussion paper), due to the overestimation of fires in China, Mongolia, Kazakhstan, the Middle East, and central U.S., where large fractions of grassland coverage were prescribed by the used land cover map in the model. We have discussed the likely too high grassland fire spread rate in the discussion paper (section 4.2.3) in these regions.

Further, we tested the modification of grassland fuel bulk density proposed by Pfeiffer et al. (2013), to prescribe the grassland fuel bulk density as a function of the 20 yr running mean of the annual sum of degree-days on a 5°C base. We rerun the simulation for the period of 1997-2006 by implementing this modification in the model. The fuel bulk density for the ground dead fuel after the modification generally increased for the extra-subtropical region (Figure C1), and the simulated burned area for the same region generally decreased (Figure C2). This partly alleviates the overestimation of fires between 30~50°N. However we found the simulated burned area for 50~75°N has been greatly reduced as well (10.5 Mha yr^{-1} by GFED3.1 vs. 4.3 Mha yr^{-1} by ORCHIDEE after modification), and the global total burned area has been reduced from 329 Mha yr^{-1} to 289 Mha yr^{-1} (i.e., the lower end of the burned area by different data in Table 1 of the discussion paper). This indicates that simultaneous changes are needed in both boreal and temperate regions (especially grassland) to allow a decent simulation of the model for the two regions. Considering that the simulated global burned area has been greatly reduced after the modification of the grass fuel bulk density, we decided to keep this modification for the future improvement of the model (but acknowledging that it could partly help resolving the issues of the overestimation for the temperate grassland fires).

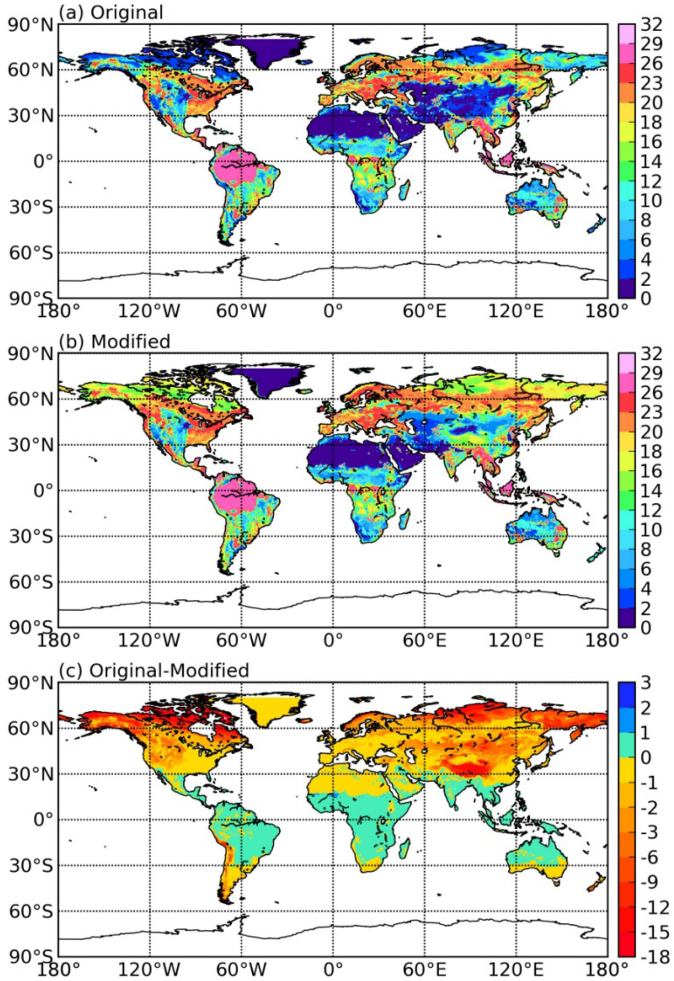

Figure C1 Ground fuel bulk density (in unit of kg mass m^{-3}) for 2001-2006 given by (a) original model simulation, (b) after modification of grass fuel bulk density, and (c) their difference.

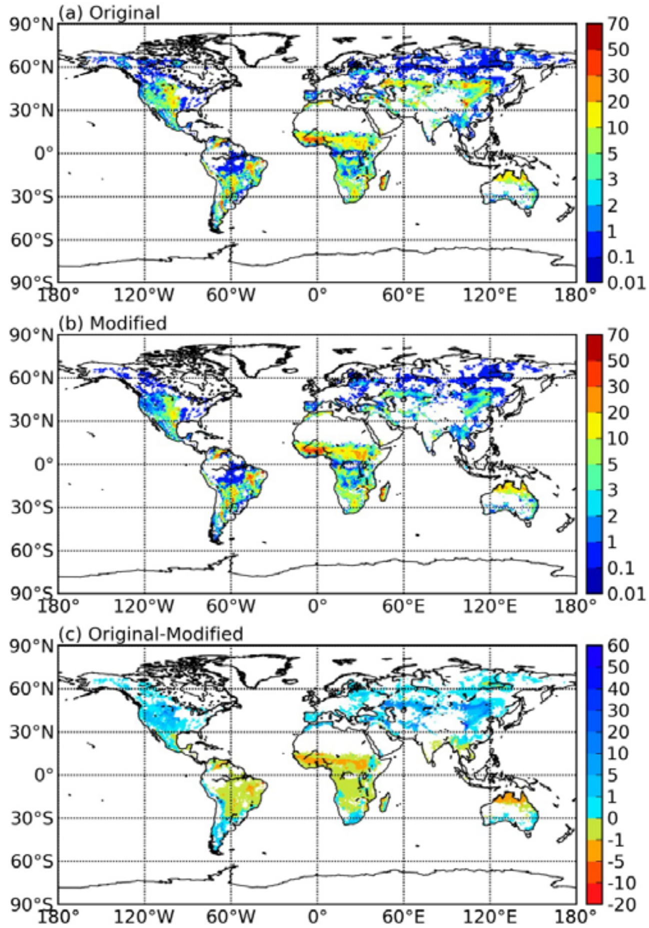

Figure C2 Mean annual burned fraction (in percentage, %) for 2001-2006 by (a) original simulation, and (b) after modification of grass fuel bulk density, and (c) their difference.

• We further found that interannual lightning variability was very important in regions with infrequent lightning but where large fires do occur, e.g., in the boreal forest and tundra regions of the Northern Hemisphere. A justification why the authors decided to ignore interannual variability in lightning and a clear call to include this in the future should be included.

[Response] We replicated the method as described in Pfeiffer et al. (2013, Equation 1 on Page 649) and produced the CAPE-derived lightning data with interannual variability for 1901-2011, and rerun the whole global simulation by using this new dataset, combined with the spatial a(ND) dataset (Thonicke et al., 2010) which is used in the human ignition equation (Equation 1 in the discussion paper, Page 2382). Besides, we have also done a separate simulation for Alaska by using the local ALDS lighting data, in order to examine the simulation improvement by using this ground-based observation data.

We found the greatest model-observation agreement for 1986-2011 could only be achieved when the model is driven by ALDS lightning data (the Pearson correlation coefficient of annual burned area between the model and Alaskan fire agency data increased from 0.19 to 0.5). And, using the new CAPE-derived lighting data only marginally improved the model-observation agreement for the same period (correlation increased from 0.19 to 0.22). For 1950-2011, the model-observation agreement slightly decreased after shifting to the new CAPE-derived lighting data (correlation coefficient changed from 0.41 to 0.37).

We systematically examined the change in the model-observation agreement for different regions and different time spans when shifting from the mean annual static lighting data to the CAPE-derived data. The agreement of simulated burned area with the observation for 1950-2011 for the boreal North America (i.e., US Alaska + Canada) generally decreased after shifting to the CAPE-derived data, either on annual or decadal basis. Over the 20th century, the shifting of lightning data decreased the agreement of simulated decadal burned area with the Mouillot and Field (2005) reconstruction for half of the 14 regions and increased for the other half. Over 1997-2009 when the observation data by the GFED3.1 is more credible than the 20th century reconstruction, using the new data decreased the agreement of annual simulated and observed burned area for the globe and for most of the regions.

In summary, the CAPE-derived lightning data does not systematically improve the model performance. This could be due to several reasons including the errors in the method to reconstruct the lightning data, the errors in the CAPE data, and model internal uncertainties. We thus finally decided to keep the mean annual lighting data in the present version of the model. However this issue is worth more detailed investigation and will be considered in the future model improvement. For detailed information regarding the comparison of the simulations using the static and CAPE-derived lighting data, please refer to the "***Response supplement material***" (at the end of this document).

References:

Lasslop, G., Thonicke, K. and Kloster, S.: SPITFIRE within the MPI Earth system model: Model development and evaluation, J. Adv. Model. Earth Syst., 06, doi:10.1002/2013MS000284, 2014.

Scholes, Robert J., Sally Archibald, and Graham von MALTITZ. "Emissions from fire in Sub-Saharan Africa: the magnitude of sources, their variability and uncertainty." Global Environmental Research 15.1 (2011): 53-63.

Response supplement material

1. Reconstructed lightning flashes with interannual variability

The interannual variability of lightning flashes is interpolated form the average monthly satellite observed lightning flashes of LIS/OTD data (http://gcmd.nasa.gov/records/GCMD_lohrmc.html), by using the interannual variability of the Convective Potential Available Energy (CAPE) during the 20th century as simulated from by the 20th Century Reanalysis Project. The interpolation is done by following the method of Pfeiffer et al. (2013, Equation 1 on Page 649).

$$l_{\mathrm{m}} = \begin{cases} \mathrm{LISOTD_m}\,(1+9\mathrm{CAPE_{anom}}), & \mathrm{CAPE_{anom}} \geq 0 \\ \mathrm{LISOTD_m}\,(1+0.99\mathrm{CAPE_{anom}}), & \mathrm{CAPE_{anom}} < 0 \end{cases} .$$

where l_m the monthly lightning flash numbers for a given month, $CAPE_{anom}$ is CAPE anomaly for the concerned month being normalized to (-1,1) for 1901-2011.

We first compared the reconstructed lightning flashes with the observation by the Alaskan Lightning Detection System for 1986-2011 (Figure 1). Their correlation coefficient is 0.48 (data not detrended).

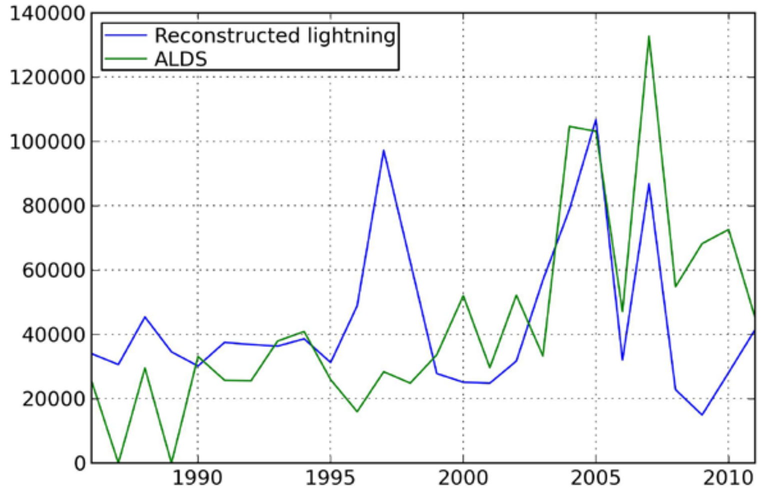

Figure 1. The reconstructed lightning flashes compared with the lightning flashes observed by the Alaskan Lightning Detection System (ALDS) for 1986-2011. To facilitate the comparison of interannual variability, the mean annual lightning numbers of reconstructed CAPE-derived data are adjusted to have the same mean annual lightning flashes as observed by ALDS.

2. Compare the simulated burned area with observation data by using different lightning input data

After the reconstruction of the interannual lightning flashes, we launched a global simulation for 1901-2011 by using the new lightning data with the human ignition parameters of a(ND) (Equation 1 in the discussion paper, Page 2382) as the spatial dataset used in Thonicke et al. (2010). This simulation is denoted as "ORCHIDEE - IAVLightn", and another simulation with mean annual lighting data and the spatial a(ND) dataset is denoted as "ORCHIDEE - CONLightn". Note that the reconstruction of interannual lightning data changed the total amount of flashes, so a constant scaling factor (0.53) has been applied in the "ORCHIDEE - CONLightn" simulation, to ensure on the global scale, the same lighting ignition efficiency factor (0.03) in the original simulation to be maintained (i.e., on the global scale, the mean annual potential lighting flashes available for ignition do not change) over 1901-2011.

Furthermore, we launched a third simulation for Alaska for 1986-2011, using the observed ALDS lightning flashes as input data, and this simulated is denoted as "ORCHIDEE - ALDS". The third simulation allows investigating the simulation improvement by using the ground-based observation of lightning flashes.

2.1 Compare burned area over Alaska

The simulated burned area over 1986-2011 is compared with GFED3.1 burned area data and the burned area by Alaskan fire agency, by using the Pearson correlation coefficient (r-value). The results are shown in Table 1. The increase in r-value (with the Alaskan fire agency data) by shifting from "CONLightn" to "IAVLightn" is very small (0.19 to 0.22). The r-value between simulated BA with the fire agency BA is the highest for the simulation using the ALDS input (0.5), though still lower than that of 0.66 by Pfeiffer et al. (2013) for the "Intermontane Boreal" ecoregion of Alaska who used the same lightning input (the r-value is derived by picking up the data from the Fig. 7 on Page 663 of Pfeiffer et al., 2013). Over 1950-2011, the r-value decreased from 0.41 for "ORCHIDEE - CONLightn" simulation to 0.37 for "ORCHIDEE - IAVLightn" simulation.

We found that using the CAPE-derived interannual lightning data only marginally improved the BA simulation for Alaska for 1986-2011, but using the ground-based observation of lightning data did greatly improved the simulation.

Table 1 Pearson correlation coefficient (r-value) for different annual simulated burned area data with the observation data by the Alaskan fire agency; and the r-value for different data with the ALDS observed flashes.

	1950-2011	1986-2011	Correlation with Alaskan ALDS lightning flashes (1986-2011)
Alaskan Fire Agency	1.00	1.00	0.55
GFED3.1		0.98	0.58
ORCHIDEE - CONLightn	0.41	**0.19**	0.20
ORCHIDEE - ALDS		0.50	0.62
ORCHIDEE - IAVLightn	0.37	**0.22**	0.50

2.2 Compare the simulated burned area with the observation for boreal North America (Alaska, US + Canada)

We examined the agreement between the simulated and observed BA for the two global ORCHIDEE simulations (with CONLightn and IAVLightn) for the boreal North America (Alaska, US + Canada). Burned area in this region is known to be dominated by lightning sources, and thus we expect the improvement in the simulation is expected to occur for this region. We used both the annual fire agency burned area data and the decadal Mouillot and Field (2005) as the observation data. The r-value between different data are shown in Table 2. Surprisingly, for all r-values, the ones by "ORCHIDEE- IAVLightn" is lower than that by "ORCHIDEE - CONLightn", suggesting that ***shifting from mean annual lighting data to CAPE-derived lightning data has generally decreased the model-observation agreement in this region.***

Table 2 The Pearson correlation coefficient (r-value) for the period after 1950 in terms of BA by different data (because after 1950 the fire agency data began to exist). The ***bold italic numbers*** indicate that the agreement with fire agency data deteriorated after shifting from "CONLightn" to "IAVLightn".

	ORCHIDEE - CONLightn	ORCHIDEE - IAVLightn
Annual correlation (n=61)		
ORCHIDEE ~ Fire Agency	***0.44***	***0.41***
ORCHIDEE ~ Mouillot & Field (2005)	***0.57***	***0.44***
Mouillot & Field (2005) ~ Fire Agency	0.92	0.92
Decade correlation (n=6)		
ORCHIDEE ~ Fire Agency	***0.42***	***0.27***
ORCHIDEE ~ Mouillot & Field (2005)	***0.81***	***0.62***
Mouillot & Field (2005) ~ Fire Agency	0.91	0.91

2.3 Compare the simulated burned area with the observation over the 20th century for different Mouillot & Field (2005) regions

We compared the decadal r-value over the 20th century with the Mouillot and Field (2005) reconstructed BA data as shown in Table 3. When examining the r-value for different regions, for some regions the BA are rather poorly simulated by the model with negative r-values (indicating anti-phase between model and observation). Over the whole globe, the r-value after shifting to IAVLightn slightly decreased (by 0.1). Of the 14 region, the r-values decreased after shifting to IAVLightn for 6 regions, with 2 regions showing no change in r-value, and 6 regions with increase in r-value. ***On the global scale, the model-observation agreement decreased after shifting to the CAPE-derived lightning data, and for half the regions the agreement increased and the other half decreased.***

Table 3 The Pearson correlation coefficient between simulated decadal BA and Mouillot and Field (2005) reconstructed BA over the 20th century (n=11). The negative r-values (poor simulation and anti-phase between model and data) and the decrease in r-value after shifting to IAVLightn are shown in red.

	CONLightn (r1)	IAVLightn (r2)	Improvement (r2-r1)
Global	0.6	0.5	-0.1
Australia	-0.4	-0.5	-0.1
BONA	-0.4	-0.5	-0.1
BOAS	-0.1	0.3	0.4
India	0.8	0.6	-0.2
SouthEastAsia	0.0	0.4	0.4
CentralAsia	0.4	0.3	-0.1

WestUS	-0.6	-0.9	-0.3
EastUS	0.1	0.4	0.3
EastAsia	-0.6	-0.7	-0.1
MiddleEastNorthAfrica	-0.6	-0.5	0.1
Africa	-0.5	0.0	0.5
CentralSouthAmerica	0.8	0.8	0.0
SouthAmerica	-0.6	-0.2	0.4
Europe	0.1	0.1	0.0

2.4 Compare the annual simulated burned area with GFED3.1 data for 1997-2009 for the 14 GFED regions

The Pearson correlation coefficients between annual simulated BA with GFED3.1 BA have been calculated for different GFED regions and the globe for simulations with CONLightn and IAVLightn (Table 4). The annual time series of burned area are shown in Figure 2. ***Over the globe, the model-observation agreement decreased, and for only two out of the 14 regions, the r-value increased after shifting to IAVLightn.***

Table 4 The Person correlation coefficient (r-value) between annual simulated BA with the GFED3.1 data for different GFED regions. The negative r-values (i.e., poor simulation of model) and the decrease in r-value after shifting to IAVLightn are shown in red.

	CONLightn (r1)	IAVLightn (r2)	Improvement (r2-r1)
Global	0.5	0.3	-0.2
BONA*	0.5	0.7	0.2
TENA	0.3	0.1	-0.2
CEAM	0.2	-0.1	-0.3
NHSA	-0.1	0.0	0.2
SHSA	0.3	-0.5	-0.9
EURO	-0.1	-0.1	0.0
MIDE	0.3	0.1	-0.2
NHAF	0.2	-0.2	-0.3
SHAF	0.0	0.0	0.0
BOAS	0.4	0.0	-0.4
SEAS	-0.1	-0.4	-0.3
CEAS	0.2	0.0	-0.2
EQAS	1.0	1.0	0.0
AUST	0.2	-0.1	-0.3

* This is not in contradiction with results presented in Section 2.2 as the spatial extend of boreal North America and the BONA here are slightly different. The BONA includes part of the western US where the model overestimated BA.

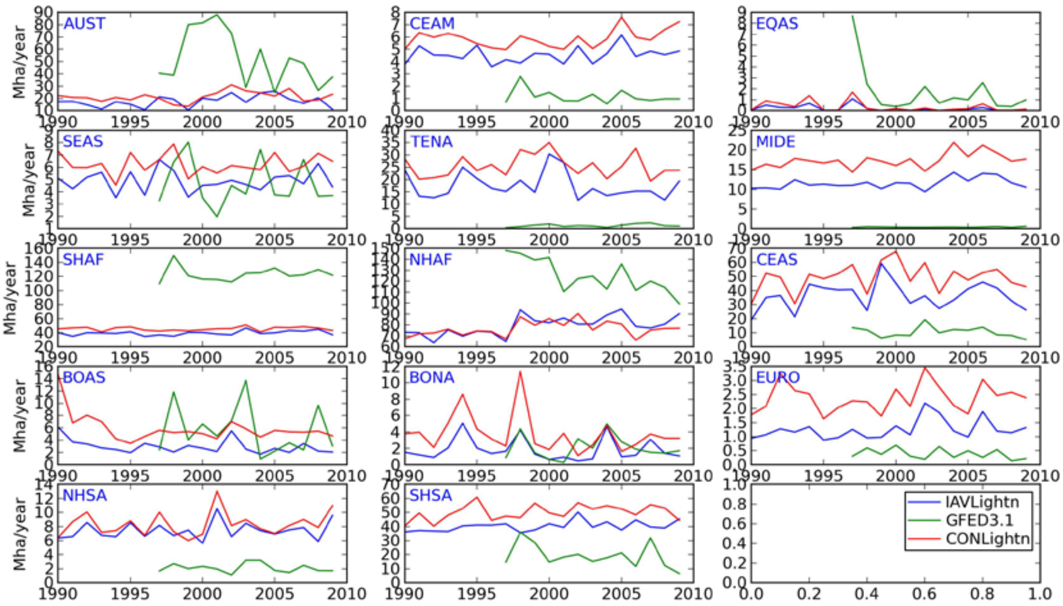

Figure 2 The annual BA time series for different GFED regions for 1997-2009 by GFED3.1 data, and the two model simulations ("ORCHIDEE - CONLightn" and "ORCHIDEE - IAVLightn").

2.5 Compare simulated global BA with GFED3.1 data

The total global BA is 273 Mha yr^{-1} according to "ORCHIDEE - IAVLightn" simulation for 1997-2009 (compared with 342 Mha yr^{-1} for "ORCHIDEE - CONLightn" and 349 Mha yr^{-1} for GFED3.1). Figure 3 shows the annual BA time series of ORCHIDEE and GFED3.1, with the r-value of linearly detrended annual time series between "ORCHIDEE - IAVLightn" and GFED3.1 is 0.46 (compared with 0.57 between "ORCHIDEE - CONLightn" and GFED3.1). There is no significant change in the spatial distribution of fires (pixel-to-pixel correlation between "ORCHIDEE - IAVLightn" and GFED3.1 is 0.481, and 0.475 between "ORCHIDEE - CONLightn" and GFED3.1). ***Thus if the global total potential available lightning ignitions over 1901-2011 were conserved in the simulation, the simulated global burned area decreased from 342 to 273 Mha yr^{-1} for 1997-2009 when shifting to the CAPE-derived lighting data, and the model-GFED3.1 agreement in the global burned area interannual variability decreased.***

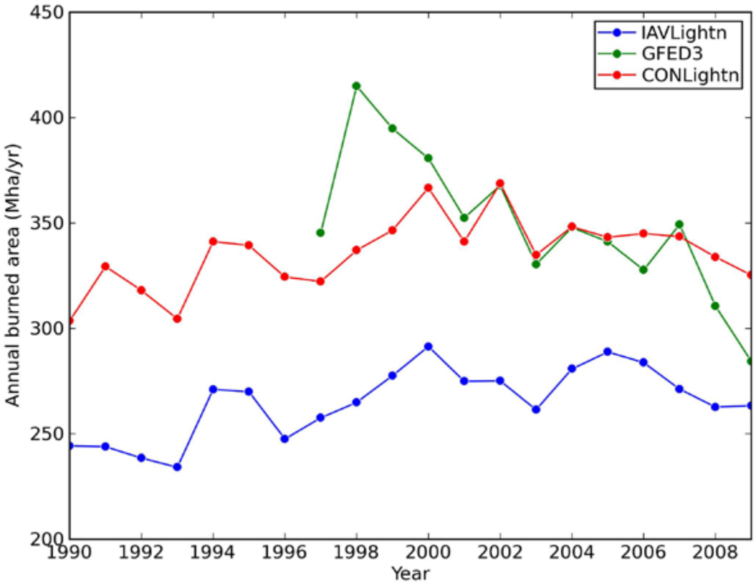

Figure 3 Annual global burned area by model simulation and as given by GFED3.1 data for 1990-2009.

3. Summary

We have followed the method proposed by Pfeiffer et al. (2013) and reconstructed the total lighting flashes with interannual variability for 1901-2011 by using the CAPE data. The new CAPE-derived lightning data moderately agreed with the ground observations of lightning flashes for Alaska for 1986-2011. However, the model-observation agreement for the burned area in Alaska for 1986-2011 has only been marginally improved by using the new CAPE-derived lighting data, compared with repeating the mean annual lightning data without interannual variability being included. For 1950-2011, the model-observation agreement slightly decreased after shifting to the new CAPE-derived lighting data. Large improvement in the simulation was found when the model was directly driven by the locally observed lighting data.

The agreement of simulated burned area with the observation data for 1950-2011 for the boreal North America (i.e., US Alaska + Canada) generally decreased after shifting to the CAPE-derived lightning data, either on annual or decadal basis. Over the 20th century, the shifting of lightning data decreased the agreement of simulated decadal burned area with the Mouillot and Field (2005) reconstruction for half of the 14 regions and increased for the other half. Especially, over 1997-2009 when the observation data by the GFED3.1 is more credible than the 20th century reconstruction, shifting of the lightning data decreased the agreement of annual simulated and observed burned area for the globe and for most of the regions.

The fact that the CAPE-derived lightning data does not systematically improve the model performance could be linked with several explanations. First, despite the physical linkage between the CAPE (atmospheric instability) and the lightning activity, the approach (equation) used here might not apply for all the regions of the globe, as it's mainly derived by the lightning observation in Alaska. Second, the errors in the CAPE data provided by the 20th Century Reanalysis Project might also contribute. Third, the uncertainties of internal model processes might have counteracted some of the expected improvement gains. For example, in Alaska, the complete replacement by local lightning observations only increased the model-observation correlation from 0.19 to 0.5, while less improvement in the lighting input data (the correlation of 0.48 between

ALDS and CAPE lightning data could be considered as an improvement in the input data compared with the otherwise mean annual lighting data) leads to nearly negligible improvement in the simulation result (r-value 0.19 to 0.22).