MS Title: Future projections of Siberian wildfire and aerosol emissions

Authors: Reza Kusuma Nurrohman et al

Author's response to the Anonymous referee #2

General Comments

The author's revisions have improved the overall quality of the manuscript. In particular, I appreciate that the authors first evaluate model performance before assessing the future projections. The incorporation of a fire module into a DGVM is an important and non-trivial task and I would like to congratulate the authors on having achieved this. However, the manuscript still reads more like a report than a scientific paper. This is because the authors tend to document all of their findings, rather than focusing on the more interesting ones. While the approach is thorough, it makes the manuscript hard to read. The authors have addressed most of my previous comments to my satisfaction. However, I still have a number of comments below for the revised version of the manuscript. I hope you find my comments useful.

Response:

Thank you for your thoughtful and encouraging feedback on our revised manuscript. We are pleased to hear that you found our evaluation of the model performance before assessing future projections to be an improvement. We appreciate your recognition of the complexities involved in incorporating a fire module into a DGVM, and we are grateful for your congratulations.

We understand your concern that the manuscript still reads more like a report than a scientific paper due to the comprehensive documentation of our findings. We acknowledge that focusing on the most interesting and relevant results would improve readability and overall presentation. We have discussed this matter internally with other co-authors, we wrote down most of all our findings because we think it is important to prove that what we mentioned in the main manuscript is scientifically validated, which covers from the initial to the end of research stage. However, we have separated the main findings in the main manuscript, while the supporting data and information are separated in the Supplement so that readers can easily find well-documented supporting information online in the Supplement file. in this second revision stage, we slightly reduced the general information (reducing the introduction section and moving some information in the methodology section to the supplement).

We take your comments into careful consideration and make the necessary adjustments to streamline the manuscript. Specifically, we will highlight the key findings and their implications while reducing the emphasis on less critical details to enhance the manuscript's clarity and engagement.

Thank you again for your valuable feedback and for acknowledging the improvements we have made. We are very grateful for the reviews you gave from the first and second stages, it is very constructive and improves the quality of our manuscript. We are committed to further

revising our manuscript in response to your comments and hope that the next version will meet your expectations.

Update: July 17, 2024

I wanted to inform you that we identified an incorrect parameter setting in our future simulation, when attempting input data flow tracing last month. Consequently, we have conducted a comprehensive re-simulation following the protocol outlined in the manuscript.

All your suggestions have been implemented accordingly. However, it is possible that there may be some adjustments in the manuscript due to varying trend results observed post re-simulation.

We sincerely appreciate your continued support and guidance throughout the review process. Your feedback has been invaluable to improving our manuscript.

Thank you once again for your assistance.

Detailed Comments

L1 The title "Future projections of Siberian wildfire and aerosol emissions by process-based ecosystem model" is grammatically incorrect. It would be "produced by" or "made by", or "conducted with a". Personally, I would reduce the title to "Future Projections of Siberian Wildfire and Aerosol Emissions".

Response:

I apologize for the incorrect grammar in the title. We agree that your suggested title, "Future Projections of Siberian Wildfire and Aerosol Emissions," is clearer and more effective. We will change the title of the manuscript according to your suggestion. Thank you for your detailed review and constructive suggestions.

L5 Replace "Fires" with "Wildfires"

Response:

Has been adjusted: **L14** Wildfires are among…

L18 You don’t want your abstract to be wordy. Delete non-essential info, such as "spatially explicit individual-based"

Response:

Has been adjusted: **L18 …** fire module into the dynamic global vegetation model (SEIB-DGVM)...

L21 Revise grammar

Response:

The grammar has been revised: **L21**

The model is able to reproduce historical data well compared to benchmark datasets. Based on the spatial validation, the results are as follows: Aboveground biomass (R^2=0.43, RMSE=21.9 Mg ha^{-1}), burned fraction (R^2=0.75, RMSE=0.01), burned area (R^2=0.609, RMSE=690 ha), dry matter emission (R^2=0.63, RMSE=0.01 Kg DM m^{-2}), CO_2 emissions (R^2=0.64, RMSE=60.9Tg).

L21 Avoid acronyms in abstract (other than R^2 and RMSE). If you need them, you need to spell them out first, e.g. AGB. In this context I would omit the names of the reference data sets, such as GFED4s.

Response:

Has been adjusted: **L21**

Based on the spatial validation, the results are as follows: Aboveground biomass (R^2=0.43, RMSE=21.9 Mg ha^{-1}), burned fraction (R^2=0.75, RMSE=0.01), burned area (R^2=0.609, RMSE=690 ha), dry matter emission (R^2=0.63, RMSE=0.01 Kg DM m^{-2}), CO_2 emissions (R^2=0.64, RMSE=60.9Tg).

R^2 and RMSE value of CO_2 emissions validation written in abstract is the average validation value from GFED4s and GBEI.

L24 What "data"? Also, does "numerically" refer to spatial mean values? Rewrite to omit ambiguity.

Response:

Data= model output
Numerically refer to the numerical values derived (extracted) from spatial data. Yes, mostly we compare with the benchmark dataset as mean values.

Thank you very much for the detailed review and suggestion. Now, has been adjusted: **L24**

Overall, the model is able to produce output with spatial distribution patterns similar to the benchmark dataset, with an average similarity of 61.8%. Furthermore, based on the comparison of mean values with the benchmark datasets, the model produces high accuracy, amounting to 99%.

L26 Replace "climate scenario" with "climate change scenario"

Response:

Has been adjusted

L27 Rather than the increase rate, can you please provide the relative change between 20-year mean historical period against 20-year future period? A relative change between two periods is more intuitive than an increase rate.

Response:

Thank you for the suggestion, has been adjusted as follow

We estimated that the CO_2, CO, $PM_{2.5}$, total particulate matter (TPM), and total particulate carbon (TPC) emissions in Siberia in 20-year mean historical period (2000-2020) will increase relatively by 43.68 ± 1.1, 3.5 ± 0.09, 0.56 ± 0.015, 0.43 ± 0.011, 0.3 ± 0.008 Tg species $year^{-1}$, respectively in the 20-year future period (2081-2100) under the Representative Concentration Pathways 8.5.

L29 What fraction of trees is this? How does this fraction compare to the historical run? I am asking these questions because from the absolute numbers it is not clear how large the impact is. It is easier to grasp when you write for instance, that the amount of trees burnt increases by a factor of three.

Response:

This is the "number of tree/ tree density" variable that produced by our model (unit: tree ha^{-1}). Tree mortality in SEIB-DGVM consist of background mortality (growth efficiency), heat stress, bioclimatic limit, and due to the wildfire (Sato et al, 2007).

We obtained the mentioned value in **L29** is under fire-on and fire-off simulations to make sure the produced variable is affected (killed) by wildfire only. In addition, we ran using all climate scenarios and repeated 5 times (same protocols and ran in the same simulation-time with other produced variables). This variable is described in section 3.6. We compared the estimated value in the future simulation under RCP8.5 with the historical value (Figure S25.c).

We understand that the suggestion you give will be easier to understand. However, if we state in a factor, the number of tree burnt increases by a factor of 1.08. To make it easier for the reader, we decide to write it as percentage as follows: **L27**

"Under the same climate scenario and period comparison, we estimated that the number of trees burnt increases by 108%, resulting in a 319.3 g C m^{-2} $year^{-1}$ loss of net primary production (NPP)."

L43 What does "human activity" refer to in this context?

Response:

In this context, human activity refers to human activity using fire for land management.

We have adjusted the sentence to be as follows:

.. and human activity by using fire for land management (e.g. use of fire as a tool in the deforestation process) (Hantson et al., 2016; Archibald et al., 2013; Morton et al., 2008).

L49 What is "global mean CO_2 emission intensity" referring to? Are you referring to the annual rate of global total CO_2 emissions? Does "NS" refer to Northern Hemispheric Summer?

Response:

Global mean CO_2 emission intensity refers to global CO_2 emissions per unit of area burned.

NS refers to non-significant.

However, in this revision stage we would like to remove this information, we just realized that we misplaced this information. We apologize for our mistake and we're grateful for the detailed review.

Below is the paragraph from the information we cited.

"On the basis of our analysis of the MOPITT CO observations and atmospheric inversions,

we estimate the global fire CO_2 emissions to be 1.8 Gt C year^{-1}, on average, during 2000–2019, with a non-significant decreasing trend of −0.5 ± 0.8% year^{-1} (95% confidence interval; purple curve in Fig. 1A). The quasi-stable emissions combined with a significant decline in global burned areas (−1.6 ± 0.4% year^{-1}; orange curve in Fig. 1A) suggest that the global mean emission intensity (i.e., CO_2 emissions per unit of area burned) has increased by 0.9 ± 0.9% year^{-1} since 2000 (purple curve in Fig. 1B) (Zheng et al., 2021)."

Zheng, B., Ciais, P., Chevallier, F., Chuvieco, E., Chen, Y. and Yang, H. (2021) 'Increasing forest fire emissions despite the decline in global burned area', Science Advances, 7(39). Available at: https://doi.org/10.1126/sciadv.abh2646.

L51 Why "as well"?

Response:

Previously, we wrote "as well" because at the beginning we stated that global mean CO_2 emissions are increasing, then we mentioned in Europe "as well".

We re-checked the sentence's grammar and found that it was incorrect, so we removed "as well".

Thank you for the detailed review.

L61 You write that "Prolonged exposure to high CO_2 concentrations has negative impacts on health and agriculture". Concerning health, that is indeed true but for very high concentrations of CO_2, not atmospheric concentrations. For agriculture, high levels of CO_2 can be beneficial. I think the relevant negative health impacts are more related to the emission of particular matter, rather than CO_2.

Response:

Thank you very much for your concern related to these points. Yes, we agree with your statements. We have adjusted the sentences accordingly:

a) We reorder the sentences to keep discussing the impact of increasing atmospheric CO_2 emissions at the beginning and adjusted based on the **L63** comment.

We have adjusted the sentences as follows: **L61**

"Increasing atmospheric CO_2 concentrations alter the global carbon cycle by causing global warming (Van Der Werf et al., 2006, 2010, 2017; Neto et al., 2009; Kaiser et al., 2012; Lin et al., 2013), and the resulting global warming is expected to intensify extreme fire seasons, leading to further surges in carbon emissions that significantly contribute to the global burden of greenhouse gases (fire-climate feedbacks) (Bowman et al., 2009)."

b) Agricultural impact (**L64)**

"This event also affect the agricultural sector positively and negatively depending on the region, environment, and crop types (Kimball and Idso, 1983)."

c) We stated the impact the CO_2 exposure on human health at the ground level after the previous sentence as additional information. **L66**

"Additionally, prolonged exposure to very high CO_2 concentrations at ground level has negative impacts on health (Jacobson et al., 2019). Therefore, …"

L63 This feedback is important, please elaborate.

Response:

Has been adjusted (**L61**)

L68 Revise grammar

Response:

Has been adjusted (**L70**)

L75 Explain what you mean by a negative impact.

Response:

Has been adjusted (**L79**)

Furthermore, an increase in atmospheric emissions negatively affects the climate by contributing to global warming and climate change (Randerson et al., 2006; Westerling et al., 2006; Bowman et al., 2009)

L171 Replace the underline with a bar in Equation (2) to make the notation consistent with the one used in the text.

Response:

Thank you for the detailed review, now has been adjusted (**L178**)

L172 Grid cells is plural

Response:

Has been adjusted (**L176**)

L182 Start line with "where" and please avoid using 3-nested parenthesis.

Response:

Has been adjusted (**L191**)

L187 LCT is not yet defined

Response:

Has been adjusted (**L196**)

L188 The PFT names are not yet defined, and please don't start a sentence with an acronym

Response:

The definition of PFTs has been added in Appendix A.3 and the beginning of the sentence has been adjusted (**L197**). Thank you for your suggestions.

L195 I would delete these two sentences on the verification process. I think it is self-understood that you make sure everything is working properly.

Response:

Yes, now those two sentences have been deleted (**L204**). Thank you for the suggestion.

L232 Delete superscript ("inputs^{2}")

Response:

Has been deleted after "inputs". Now, superscript 2 has been moved to "The model was run in three phases^{2}" **L242**. This is to explain the that the "simulation years^{2}" process setting in Figure 3.

L233 Why is the "MirocAR5 Base V2 dataset is generated from CRU TS3.22 climate data"? Miroc is a climate model. Do you mean that the Miroc version you used as bias-corrected with CRU? Please clarify.

Response:

Thank you very much for the suggestion. Yes, I meant that, because the historical simulation used climate data from CRU TS3.22 and the future simulation from MirocAR5 Base V3 data (correction: we used version 3). So to ensure harmonized climate input data, Miroc climate data has been bias-corrected using CRU TS3.22 data.

Thank you very much for the detailed review and constructive suggestion.

L246. The MirocAR5 Base V3 dataset has been bias-corrected with CRU TS3.22 climate data, so using these two datasets consecutively in spin-up, historical, and future simulations ensures the harmony of the input climate data.

L241 The term "saturation" does not fit here.

Response:

The "saturation" has been replaced with "equilibrium".

Adjusted sentence as follows **L256**

Another study by Arakida et al. (2021) also confirmed that a spin-up period of 100 years was sufficient for the equilibrium of the LAI, aboveground biomass, and GPP at all the study sites in Siberia.

L243 Write "The SEIB-DGVM code modifications" and revise grammar. I suggest you rewrite the sentence as two sentences.

Response:

Thank you for the detailed review. Apologize for the incorrect sentence structure, we tidied up section 2.4 by slightly changing the paragraph structure to improve the flow.

We made changes to the placement of the last paragraph sentence as follows (already applied to the revised manuscript).

SEIB-DGVM code modification are described in the section 2.2. **(deleted).**

The annual average ignition factor variables (population density and lightning flash rate) were used consistently throughout all simulation phases **(L236).**

We ran the improved model (SEIB-DGVM SPITFIRE) and the default model (SEIB-DGVM GlobFIRM) under the same protocols to equally compare and assess their fire products (Figure S3 in the Supplement)[*] **(L238).**

Simulations were run in three phases (spin-up, historical and future) and the simulation was run with the fire mode on and fire mode off to compare and assess the vegetation products during fire, and also each phase was replicated 5 times to minimize bias due to random variables in the tree morality[1]**(L239).**

In addition, we have verification stage[3] to ensures that the new input data can be read, produced, and processed properly (Rabin et al., 2017). Then, we calibrate all of the major emissions individually and sequentially with the benchmark dataset because each variable affects other variables, and we need to ensure the final output is comparable with the benchmark datasets[4]. After verifying that the new module was incorporated seamlessly, we validated the model outputs (fire, vegetation and emissions variables) by using GFED4, GFED4s, ESA Biomass CCI and GBEI benchmark datasets[5]**(L258).**

Five different types of RCP scenario climate data were used to determine the impact of fire and climate on forest structure and their interactions **(L248).**

L249 Revise grammar

Response:

Grammar has been revised.

L318 Remind the reader what this core variable is

Response:

Has been adjusted **(L326)**. The core variable of fire products is “fire probability” which affects all fire variables and their derivatives.

L375 Revise grammar

Response:

The grammar of this paragraph (**Lines 368 to 378**) has been revised. Thank you for the detailed review.

L498 Write "because it is"

Response:

Thank you, has been adjusted.

L499 You write that "Based on the comparison of results between the fire-on and fire-off simulations, the NPP variable under all of the RCP scenarios shows a downward trend with some small fluctuations". It sounds as if the difference between simulations with fires on and off reveals a trend in NPP. I am sure this is not what you mean to say, please rewrite.

Response:

Thank you for the detailed review and we’re grateful for your understanding and constructive suggestions.

We have adjusted the sentence as follows

We obtained the NPP lost variable due to wildfire from fire-on and fire-off simulations. The NPP lost variable under all RCP scenarios shows a decreasing trend with some small fluctuations **(L509)**.

L565 FDI not defined

Response:

Has been adjusted fire danger index (FDI). **L556**

L642 Replace "dan" with and"

Response:

Has been adjusted. **(L656)**

L649 Revise grammar

Response:

Has been adjusted. **(L662)**

L655 Please avoid sentences like these. Instead of copying the raw data from the table, facilitate its interpretation.

Response:

Has been adjusted **(L668)**. Thank you very much for your detailed review and valuable suggestions.

"The 20-year average simulation results of HTR variables for 2000-2020 (historical) and 2021-2040 (RCP8.5) showed the highest values compared to the average of other years, with values of 2572.86 ± 78.08 and 2534.29 ± 96.30 Tg C $year^{-1}$, respectively (Table S5). We suggest that the high HTR values during those years were due to the high decomposition rates of litter and soil organic carbon, and a decrease in the burned fraction during that period (Figure S4.d)."

L654 Replace "Heterotrophic" with "heterotrophic"

Response:

Has been adjusted. **(L667)**

L660 Does this apply to all of the RCPs that you assessed?

Response:

Yes, the simulation results under all RCP scenarios show the same trend. **(L673)**

"Overall, SEIB-DGVM SPITFIRE simulates that until the end of the 21st century, there will continue to be a weakening of the land carbon sink in Siberia under all RCP scenarios. This is also reinforced by the CESM2 model simulation, which indicates the same trend globally."

L661 Why "saturated"?

Response:

Apologies for the improper choice of words; we have adjusted it to "pronounced." **L676**

"Negative NBP extremes become more frequent and pronounced by the end of the 21st century, suggesting that terrestrial ecosystems may lose their potential to absorb anthropogenic carbon and mitigate the effects of climate change (Sharma et al., 2023)."

Figures

Figure 5 Replace "Kg" with "kg" in figure legend (here and elsewhere). Also, increase font of x-axis, and consider replacing the full month names with their first letters (J, F, M, etc.)

Response:

Figure 5 has been adjusted by adjusting the unit writing "kg" and x-axis months in 3-letter abbreviations.

Writing unit "kg" has been adjusted in all figures in the main text and supplement.

Figure 8 The burned biomass should have a time unit as well (mass per unit of area per unit of time). Add GlobFIRM and SPIFIRE to the (c) and (d) panels, respectively, such that the difference between both plots is more obvious.

Response:

Has been adjusted by adding time unit ($year^{-1}$) and adding model name labels to panels c and d. Thank you very much for the constructive suggestions.

Author's response to referee #3

The authors have made large efforts to improve the study following most of comments from reviewers. However, some concerns remain unsolved and should be responded carefully to improve the credibility of the future projection.

Response:

Thank you for recognizing the efforts we have made to improve our study in response to the reviewers' comments. We appreciate your acknowledgement of our work thus far.

We understand that some concerns remain unsolved, and we are committed to addressing them thoroughly in this review stage. Your feedback is crucial in enhancing the credibility of our future projections, and we take your comments very seriously.

Once again, thank you for your constructive feedback and for your dedication to improving the quality of our work.

1) **First,** the validation is still confusing. Fig. 2 compares the spatial distribution of burned fraction from GFED4 and the model. However, it is only the agreement of coverage instead of the locations of hotspots. As I know, most of fires are located in the eastern Siberia at a narrow band. Please show the map of GFED4, the model, and their difference separately with values indicating the spatial distribution of burned fraction.

Response:

Thank you for your detailed feedback and for pointing out the confusion regarding the validation of our model. We understand your concern about the need for a more precise comparison of the spatial distribution of burned fractions.

Apologize, perhaps the intent of Figure 2 is Figure S10 (in the supplement) which relates to the comparison of the spatial distribution of the burning fraction between GFED4s and the model.

Since the first version of our manuscript, we have visualized the spatial distribution map of the burned fraction variable. At this second revision stage, the image is in Figure S10 (in the Supplement).

Author's response to referee #3

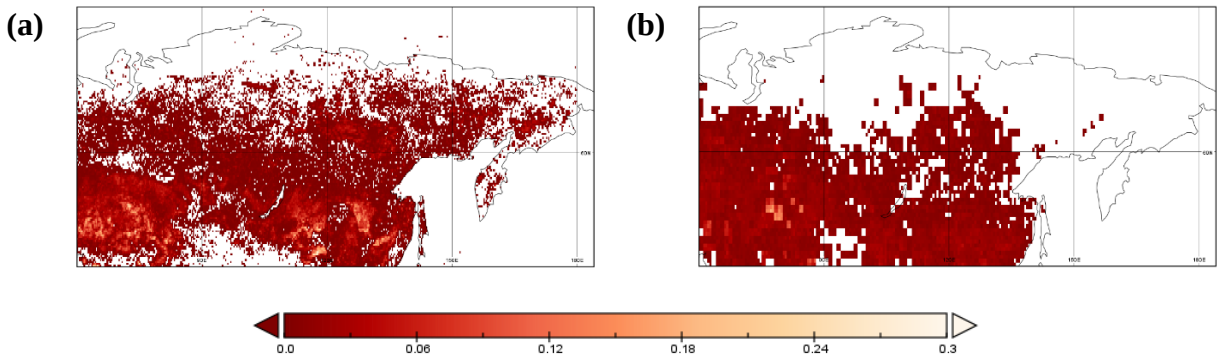

Figure S10. Spatial distribution of annual averaged (1997-2016) burned fraction variable of: **(a)** GFED4s **(b)** SEIB-DGVM SPITFIRE

Indeed, hotspot data and burned fraction data are different, but burned fraction data represents the fraction of fire in the proportion of the area (simulated each grid cell) at a certain of time. The more frequent or intense the fire occurs in the area, the higher the burned fraction value. Thus, it can be said that the comparison we have made represents all hotspots from 1997 to 2016 on a large scale in Siberia.

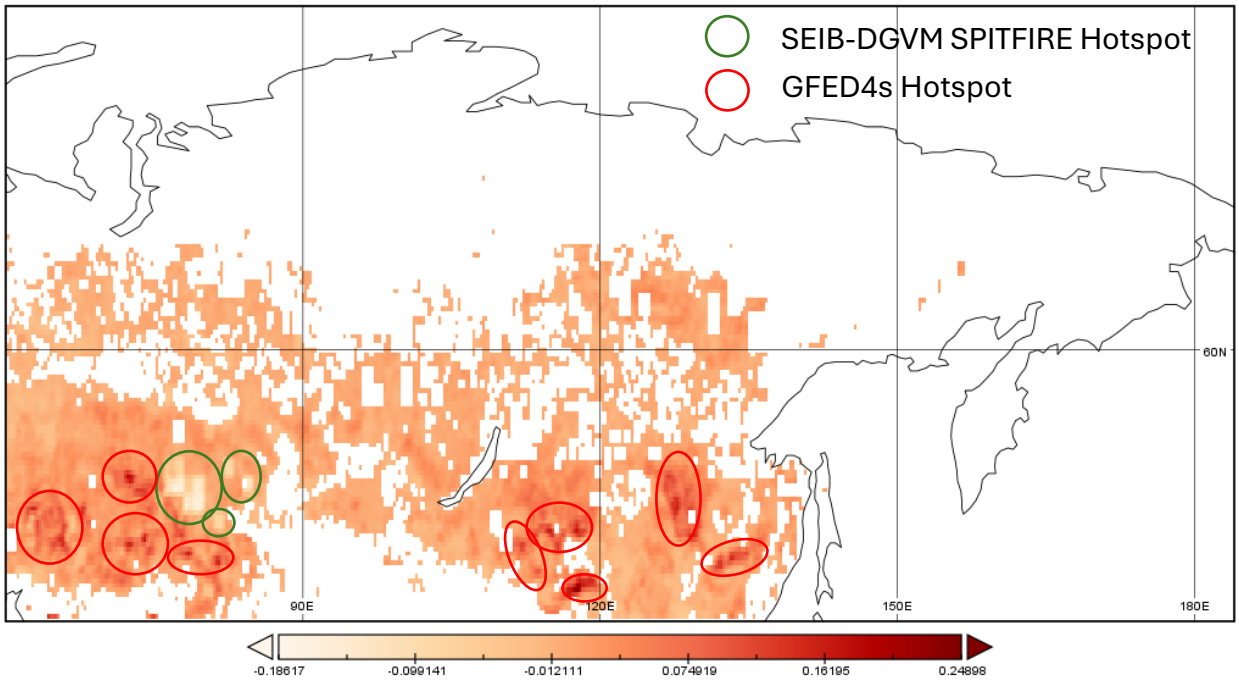

Figure rev1. Spatial distribution differences of burned fraction variables from GFED4s and SEIB-DGVM SPITFIRE (GFED4s - SEIB DGVM SPITFIRE)

Figure rev1 shows that there are hotspot differences between SEIB-DGVM SPITFIRE and GFED4s. The high negative value (-0.186) indicates the hotspot in SEIB-DGVM SPITFIRE is higher than the hotspot in GFED4s, while the high positive value indicates the hotspot in GFED4s (0.248).

The hotspots of SEIB-DGVM SPITFIRE are influenced by the fuel load variables available by default (proved by the same hotspot pattern in SEIB-DGVM default: Figure S4.a).New ignition factors (lightning: Figure S1.b and population density: Figure S1.d) affect the burned fraction spread over Siberia, which is different from the default SEIB-DGVM where no other hotspots are visible besides the green circles.

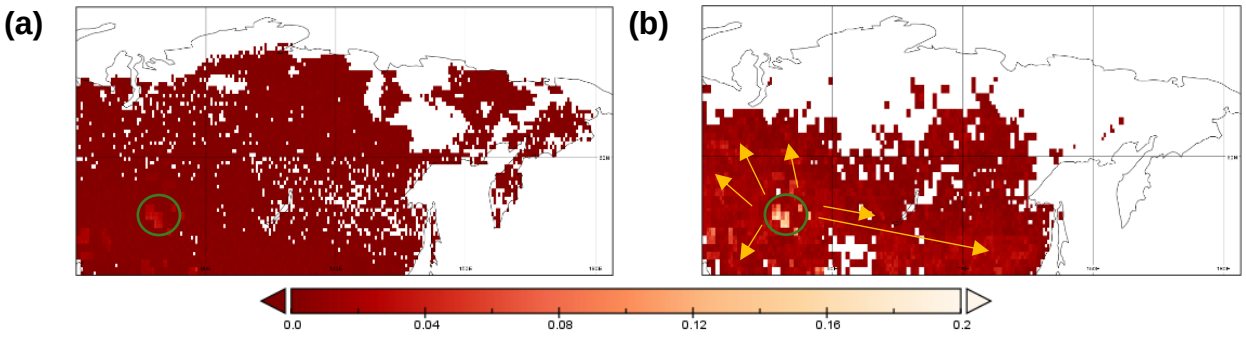

Figure S4. (a) Spatial distribution of annual averaged burned fraction of SEIB-DGVM GlobFIRM from 2006 to 2100. **(b)** Spatial distribution of annual averaged burned fraction of SEIB-DGVM SPITFIRE from 2006 to 2100. *Green circle and orange arrow is for review purposes only, isn't available in Figure S4 in the Supplement.*

Author's response to referee #3

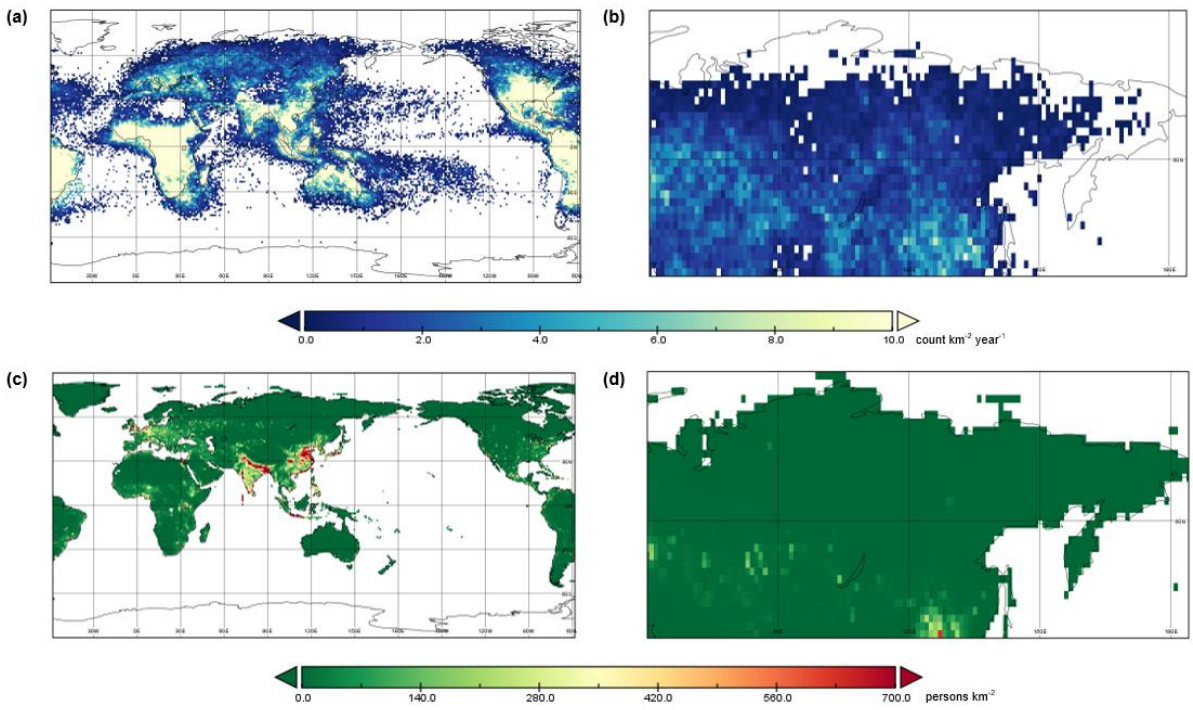

Figure S1. Spatial distribution of lightning flash rate (LIS/OTD HRFC) and population density (GPWv4) input data: **(a)** LIS/OTD HRFC global, **(b)** LIS/OTD HRFC Siberian, **(c)** GPWv4 global, **(d)** GPWv4 Siberian

We have explained in **(L359)**, that there are dynamic extreme events in GFED4s in section 3.1.3, where the current model is not able to accurately spatially simulate the existing extreme events. Currently the model is able to simulate in the long term and a fairly large area (already explained in section 4.4 model uncertainty). In the burned fraction variable, as evidenced by the very slight difference with the GFED4s data, the model broadly has a slight overestimate value of about -0.0121. In the area of eastern Siberia, as you explained there is no detectable difference, perhaps the very small fraction value in the GFED4s data is due to its location in the narrow band.

Regarding the difference in spatial distribution between the model and benchmark data (GFED4s and GFED4) in eastern Siberia, we have explained in section 4.1 Feasibility of fire simulation (**L611**).

Author's response to referee #3

2) Fig. 6 (original Fig. 9) compares the monthly fire emissions from model and GFED4. The authors provide the data link for the check of high R2 as I questioned. However, there are only 141 data samples for the period of 1997-2016 (20 years or 240 months). How are these 141 samples composed of? Furthermore, the R=0.78 is mainly due to the 0 values for both observations and models. If these zero values are removed, the R will be only ~0.3, suggesting that the model actually has low prediction of fire magnitude when the fires occur.

Response:

Thank you for your detailed feedback and for highlighting the concerns regarding Fig. 6 (original Fig. 9).

Regarding the 141 data samples, we acknowledge the need to clarify their composition. These samples represent latitude average grid-scale comparison from both dataset (SEIB-DGVM SPITFIRE and GFED4s).

We have written the source of the data comparison data in the image caption of the previous revised manuscript.

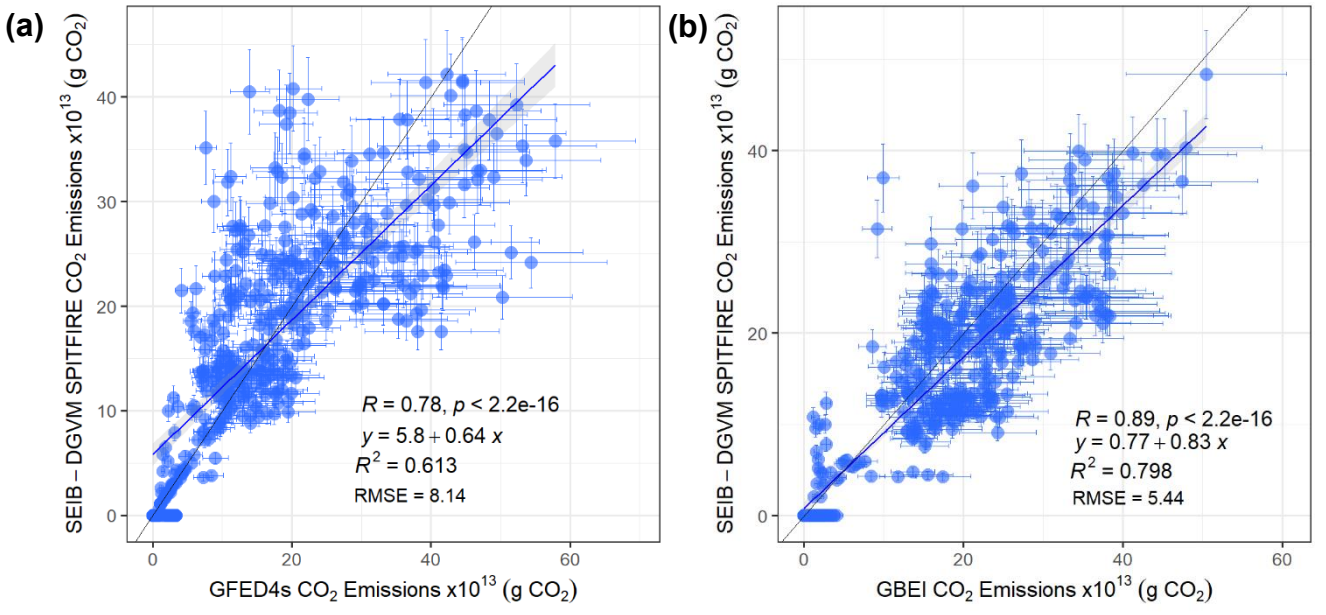

Figure 6. Latitude average spatial comparison of simulated CO_2 emissions of SEIB-DGVM SPITFIRE with GFED4s from 1997 to 2016 (**a)** and GBEI from 2001 to 2020 **(b)** dataset. Standard deviation obtained from the annual CO_2 emission data of each dataset.

Author's response to referee #3

Our opinion, the model (especially the global model: DGVM) will be very difficult to simulate on a large scale but with high accuracy on grid-level. This does not mean that we neglect accuracy, but rather that we strive for a broader level of agreement (multiple grids or regions combined). In our current study, the main limitation is still in the simulation of the distribution pattern of the fire variable, which greatly influences its derivative variables: up to the burned biomass emission variable. However, numerically (as a mean value) the model is able to produce values that are very similar (99%) to the benchmark data. This has been explained in section 4.4 Model uncertainty. The limitations of the current model are our opportunities for further development, in order to be able to produce better distribution patterns.

We used latitude average comparison to determine the average value, pattern and dynamics of variables at longitude point of view. Furthermore, in accordance of previous studies, model projections are not validated spatially at grid cell level but they validated the model output with observational data in a numerical comparison (specific area, temporal average, and only few variables). e.g. Fig. 3 Verification of the simulated length of fire season using LPJ-DGVM against observations in the sample regions (Thonicke et al., 2001), Fig. 4 Fire return intervals for the period 1987–96 derived from the national fire statistics of forest services and simulated for the same period by the LPJ-DGVM (Thonicke et al., 2001), Fig. 6. Observed (MODIS) versus simulated fire season lengths for biomes (Thonicke et al., 2010), and Fig. 8. (a) Comparison of observed (Ni, 2004) and simulated net primary production in northern China. (b) Comparison of observed (Sukhinin et al., 2004) and simulated area burnt for 1997–2002 (Thonicke et al., 2010).

In this study we compare both (numerical comparison and spatial comparison: average latitude at Siberian level and regional level) for all major variables. Therefore, our validation process is better because it covers all major variables and uses two types of validation.

We performed an apples-to-apples comparison of the model simulation results and benchmark data by comparing each grid at the average latitude. A value of 0 represents the absence of fire in the area, and the model is also able to simulate this. We believe that a good fire model is not only able to simulate fire events with high accuracy, but also able to simulate the absence of fire events, which is in complete agreement (fire event and non-fire event) with the benchmark data used.

Author's response to referee #3

3) Fig. 7 compared the PM2.5 emissions from the model and CAMS for 2004-2021 (18 years). Why there are only 12 data points on the scatter plot?

Response:

Thank you very much for the detailed review, we apologize for the wrong year in the caption.

Whole CAMS data is from 2004 to 2021 (Romanov et al., 2022). However, we only use CAMS data from 2010 to 2021 for the comparison of $PM_{2.5}$ emissions, because within that year range, both datasets show the same trend.

We have adjusted L409 and caption in Figure 7.

4) **Second,** the future projection seems unreasonable. Although no one could accurately predict future changes of fires, there are still some principles we could follow based on historical variations of boreal fires. The study shows very limited differences of future fire emissions among the four climate scenarios (Fig. 13). In addition, under the RCP8.5 to RCP2.6 scenarios, overall emissions by 2100 are projected to increase by 2.6%, 1.9%, 1.05% and 1.04% compared to 2000 emissions (Figure S28). These changes are too small to believe as future climate is quite different among the four scenarios and the RCP8.5 scenario projects an extremely warming world. The authors claimed that "the fire calculation does not directly use/consider the temperature variable. Instead, the fire variable is estimated based on the calculation of a chain of variables ranging from fuel availability fuel load (litter + aboveground biomass), moisture content…" I think the moisture content and fuel load should also be different under these climate scenarios. How the authors consider the changes of these driving factors in the projection?

Response:

Thank you for your detailed feedback on our manuscript, particularly regarding the future projections of fire emissions under different climate scenarios.

We appreciate your concerns about the small differences in future fire emissions among the four climate scenarios and the seemingly limited changes projected by 2100. We understand that this appears counterintuitive given the expected significant differences in future climate conditions, especially under the RCP8.5 scenario.

We have rechecked most of the variables described in the manuscript and show the same pattern with very little difference between RCP scenarios.

Author's response to referee #3

Since early last month, we have been meticulously tracking the flow of climate input data to ensure accurate reading, processing, and output generation.

During this tracking process, we discovered a slight misconfiguration in the reading of climate input data for our future simulations, resulting in a 30-year loop that affected our model output. We have promptly corrected this configuration and conducted a re-simulation following the protocol outlined in the manuscript.

Subsequently, we have revised all figures, tables, and explanations in both the manuscript and supplementary materials.

Regarding the projected changes, we present the latest findings as follows: "Under the RCP8.5 to RCP2.6 scenarios, the twenty-year average comparison of overall burned biomass emissions data from 2080-2100, compared to data from 2000-2020, shows projected increases of 23.87%, 27.63%, 29.34%, and 30.36%, respectively (Figure S43)."

Furthermore, in this simulation, we observed that burned biomass emissions are projected to increase from the highest to the lowest under the RCP2.6, RCP4.5, RCP6.0, and RCP8.5 scenarios, respectively.

The spatiotemporal dynamics of the biomass burning emissions under all RCP scenarios had similar patterns and trends, but they had slightly different variations in dynamics because climate affects the frequency and distribution of fires. This is evidenced by all fire variables produced by the model, from burned fraction to burned biomass emissions. In the last 20 years of the projection (2080-2100), the highest values were obtained from simulations using climate inputs RCP2.6, RCP4.5, RCP6.0, and RCP8.5. This occurs because each RCP scenario exhibits varying radiative forcing, with RCP8.5 notably experiencing the highest temperature increase (Figure S42) and also projecting the highest precipitation levels (Figure S40.b). The fuel load variable follows a corresponding order reflective of RCP forcing levels, with RCP8.5 showing the highest and RCP2.6 the lowest (Figure S40.a). However, due to increased precipitation and temperature-induced snowmelt, the moisture content of litter fractions in RCP8.5 simulations attains the highest values, contrasting with the lowest values in RCP2.6. Consequently, available fuel loads may not ignite in areas with high moisture content, leading to projections of the highest burned biomass emissions in the last 20 years of RCP climate projections (2080-2100) for RCP2.6, RCP4.5, RCP6.0, and RCP8.5, respectively.

Author's response to referee #3

We have observed that the resulting fuel load aligns with the order of RCP radiative forcing scenarios, with the highest load under RCP8.5 and the lowest under RCP2.6. Interestingly, the fuel load under the RCP8.5 simulation also exhibits a higher moisture fraction, which correlates with higher precipitation values.

This relationship is supported by the average values of the fire factor variable across scenarios: RCP8.5 (0.88), RCP6.0 (0.89), RCP4.5 (0.91), and RCP2.6 (0.92), indicating a decreasing trend in fire factor with decreasing radiative forcing.

These findings underscore the complex interactions between climate variables and fire behavior, as outlined in our manuscript. In addition, based on the variables that we have presented, it shows that the calculation flow in our fire module has run well according to the input data used and the variable calculation is well-integrated with each other.

Author's response to referee #3

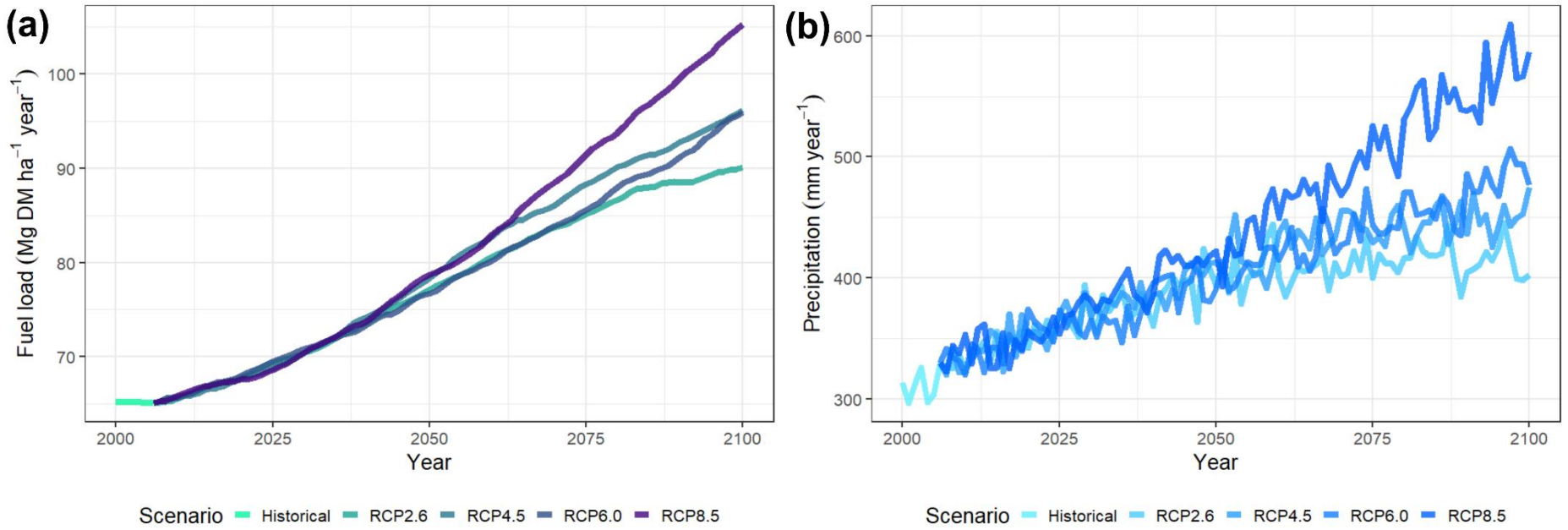

Figure S40. (a) Temporal variation of simulated SEIB-DGVM SPITFIRE fuel load in Siberia under different RCPs climate scenarios from 2000 to 2100. **(b)** Temporal variation of precipitation under different RCPs climate scenarios in Siberia from 2000 to 2100

Author's response to referee #3

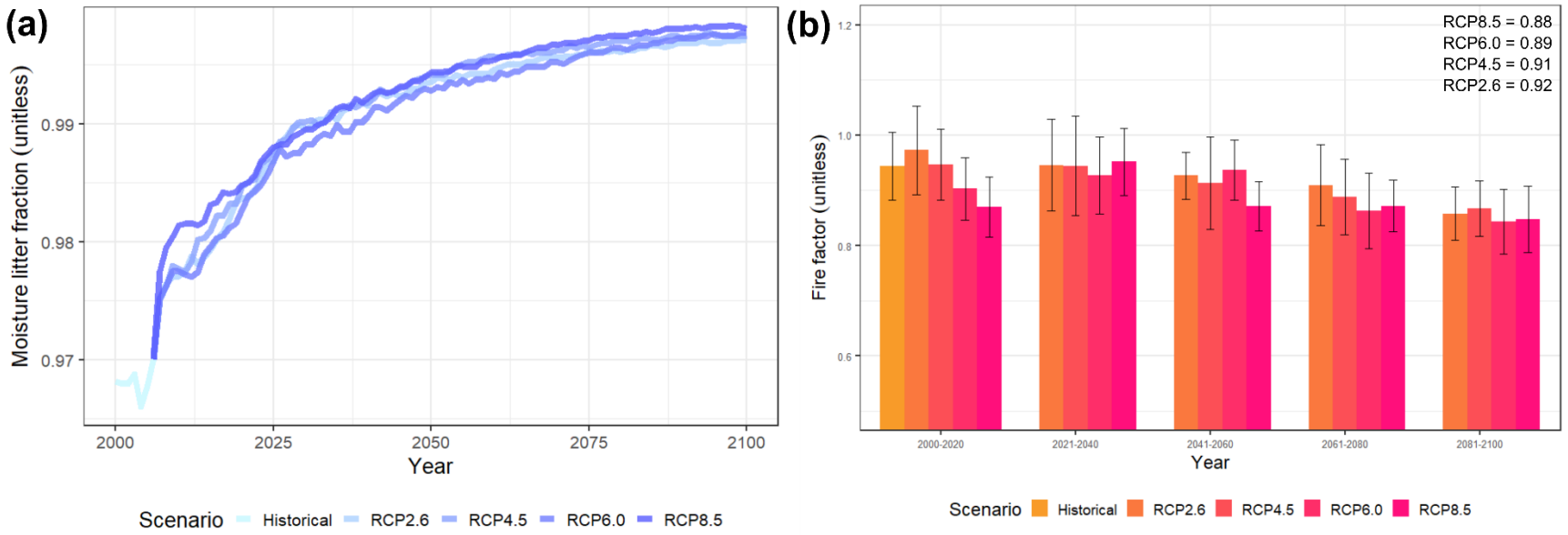

Figure S41. (a) Temporal variation of simulated SEIB-DGVM SPITFIRE moisture litter fraction in Siberia under different RCPs climate scenarios from 2000 to 2100. **(b)** Temporal variation of fire factor under different RCPs climate scenarios in Siberia from 2000 to 2100

Author's response to referee #3

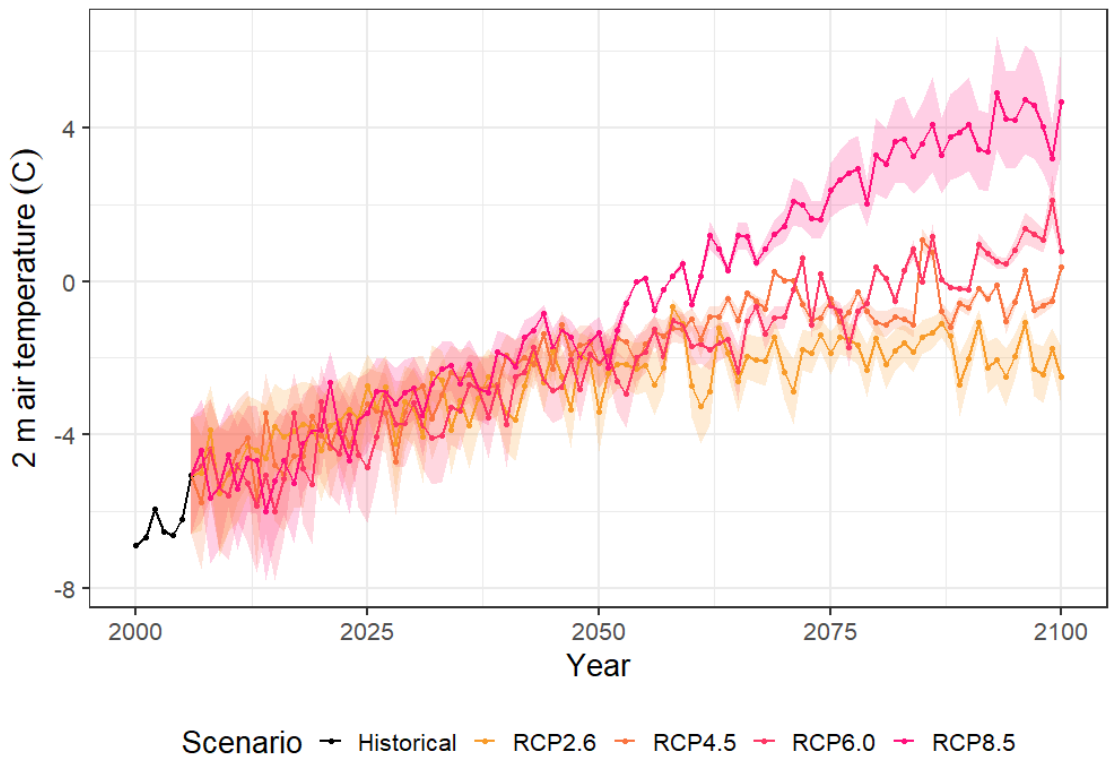

Figure S42. Temporal variation of average 2 m air temperature in Siberia under different RCPs climate scenarios from 2000 to 2100