Thank you for your comments. Please see the response below. Texts in italics are RC1’s comments. Authors’ replies are preceded by “⇒”.

This paper needs major revisions. It reports unusual responses to black carbon injections, but does not diagnose the climate response to explain why. It seems that your model does not loft the BC into the stratosphere nor rain it out, and so it persists somehow in the upper troposphere, heating it and probably evaporating clouds. Is this physically realistic? Please show the vertical distribution of the BC and clouds over the regions that experience surface warming in the first JJA. Without looking at the distribution of clouds, precipitation, and BC, how can we figure out why there is warming. Is it downward emission of longwave from the BC cloud? How is this possible if there are water clouds? The paper calls for future work on that, but this paper needs that analysis. Otherwise, the strange result is not explained.

⇒ We thank the reviewer for emphasizing the need to make the physical mechanisms more explicit. While our original submission did include diagnostics of the climate response (Sections 3.2 and 3.3), we agree that the explanation of the warming mechanism needed to be clearer and more directly linked to the spatial structure of the response. In the replies below, we have worked with the Reviewer’s comments in mind, to clarify and further explore the climate response. For example, we have emphasized changes in the cloud distribution that are of interest as well as changes in column water vapor and clear-sky surface DLRF.

⇒ In the original manuscript, we diagnosed the climate response to black carbon (BC) injection in detail in Section 3. The surface climate impacts were diagnosed in Section 3.2, and the surface energy fluxes were diagnosed in Section 3.3.

We showed that the model did loft the BC into the stratosphere in the simulations and discussed the removal of BC in the troposphere through both dry and wet deposition. For example, as we discussed in Section 3.1, the BC was lofted into the lower stratosphere (the so-called “overworld” term used in the literature on stratosphere troposphere exchange). The overworld burden for the BC24 case attained its maximum at 5.2 Tg in first year June, while the overworld burden for BC12 attained its maximum at 2.0 Tg in the same month (Fig. 1a inset in the manuscript).

In addition, we showed how the model did remove the BC in the simulations. As can be seen in Fig. 1b, 70-80% of the injected BC was removed from the atmosphere in the first year. The model can do this via either dry or wet deposition (not only via "rain out"). The treatment of dry and wet deposition in CanESM5 was described in Section 2.1.

We showed that the BC does not persist in the upper troposphere. Part of the BC was lofted into the stratospheric overworld, with this portion shown in the inset of Fig. 1a.

Another part of our description of the climate response relates to the character of the heating induced by the BC injection. While the maximum heating occurs in the stratosphere (Fig. 3b), it is indeed the case that some of the radiative heating response does descend into the upper troposphere. This downward extension of the region of radiative heating into the upper troposphere is physically realistic in our view.

⇒ One new point introduced by the Reviewer, which we had not included in the original submission, relates to the possibility of a cloud response, in particular a decline in cloud fraction in the upper troposphere. We appreciate the Reviewer's encouragement to focus more of our analysis on the regions where surface warming occurs. This has led to what we will propose as the most significant revision to the paper. As suggested, to show the vertical distribution of the BC and clouds over the regions that experience surface warming in the first JJA, we have highlighted those regions in Fig. R1 and plotted the corresponding distributions in Fig. R8. The precipitation change is plotted in Fig. R7. These figures and the analysis will be included in the revision, divided between the main body of the text and in the Appendix.

One insight we gained is that the intense downward emission of longwave from the intense warming in the lower stratosphere (Fig. 3 in the manuscript), drives warming in the first year's boreal summer (JJA) in regions that have generally low cloud fraction to start with (Fig. R4). Therefore, the changes in clouds in these relatively clear and arid regions do not appear to be a primary driver of the warming signal. We did, however, examine the cloud fraction response (Fig. R5), and it reveals significant increases in cloud fraction in northern Africa and some significant decreases in western North America and Tibet. The mechanism of the warming is not being primarily related to cloud responses.

To deepen our understanding of the clear-sky warming effects, we examined the clear-sky surface DLRF and water vapor changes. We find that the global mean clear-sky surface DLRF response is similar to that of the all-sky surface DLRF response, with the same peak in the first JJA (Fig. R2 and 2c in the manuscript). Both the clear-sky surface DLRF response and the column water vapor response are spatially similar to the increase in surface DLRF (Fig. R3, R6, and 6a in the manuscript, respectively). All three of the responses in water vapor, clear-sky surface DLRF, and all-sky surface DLRF over these land regions that warm in the first JJA are greater than those over other land regions (Fig. R3, R6, and 6a in the manuscript, respectively), suggesting that downward emission of longwave from BC aloft is being amplified by water vapor feedback for these regions in the first JJA.

⇒ The vertical distributions of BC, cloud, and water vapor are physically consistent with one another. There is BC enhancement in the troposphere over the warming regions in the first JJA, but the BC enhancement is much greater in the stratosphere (Fig. R8 first row). With upper tropospheric warming, the cloud fractions in the upper troposphere do decline for these regions, but the cloud fraction in the middle to lower troposphere increases for the northern African region (Fig. R8 second row). The specific humidity has a great percentage increase in the UTLS (Fig. R8 third row), which is consistent with the UTLS warming. The relative humidity decreases in the UTLS due to intense warming, but it increases in the middle to lower troposphere, which is consistent with the suggestion of water vapor feedback.

Thus, we find that overall, for these warming regions in the first JJA, the increased surface DLRF is associated with increased column water vapor and BC burden. This effect is consistent with the nighttime warming (Fig. A4 in the Appendix) that we discussed in the original manuscript.

While we did find a mix of increases and decreases of precipitation over the regions that warm in the first JJA (Fig. R7), the contribution of precipitating processes to the transient year-1 warming signal is not clear.

⇒ We will revise the manuscript to include a discussion of the regional water vapor, BC, and cloud responses in the Discussions and Conclusions. Additional material less relevant to the warming mechanism will be confined to the Appendix.

⇒ Once again, we appreciate the reviewer's encouragement to look at new aspects of the response. With the Reviewer's comments in mind, we have investigated additional aspects of the climate response beyond what was shown in the original submission. Based on the additional diagnostics now included, we find no evidence that the simulated response is inconsistent with our physical understanding. Therefore, we have no concern with physical realism of these simulations beyond those that generally apply to coarse resolution global models used in this field.

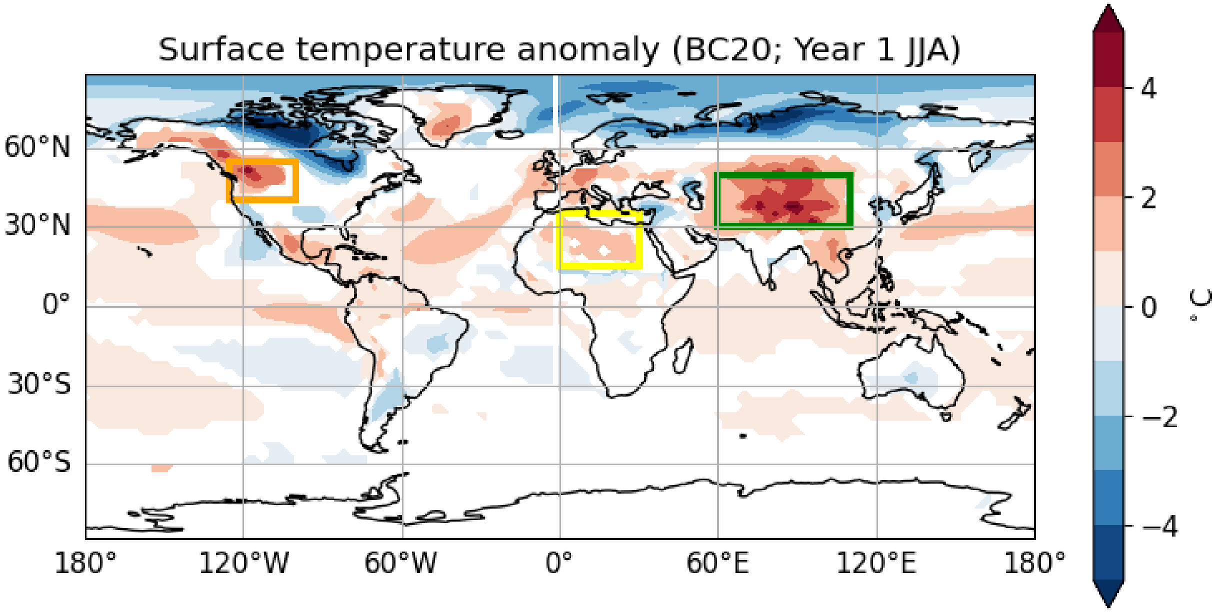

Figure R1. Response of surface temperature for BC20 in the first JJA. White patches indicate changes that are not significant at 95% confidence level using a t test.

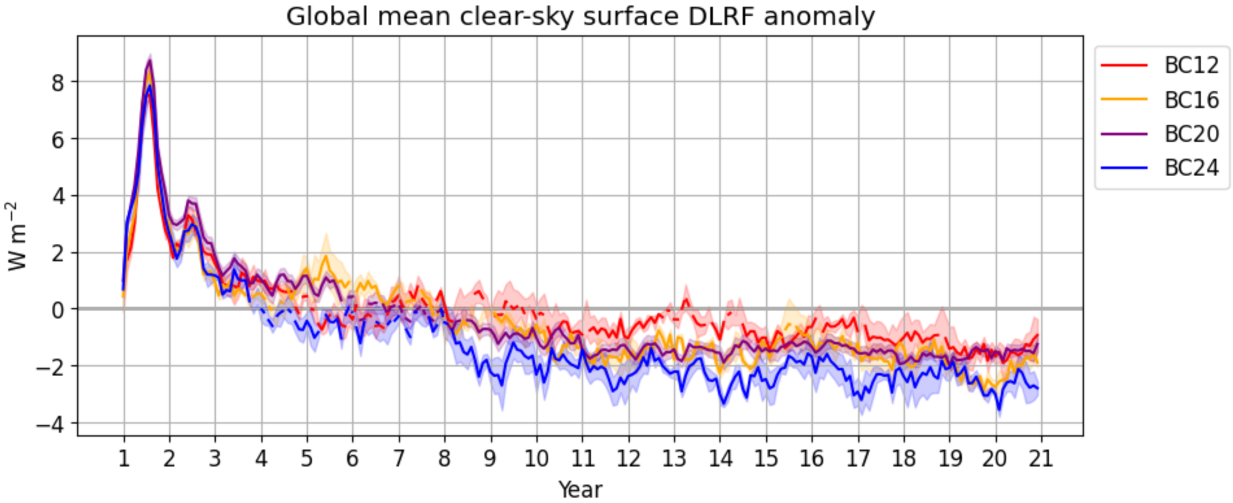

Figure R2. Monthly averaged global mean response of clear-sky surface DLRF. Shading indicates ±1 standard error of the ensemble mean. Dashed lines indicate where the standard error overlaps with the zero line.

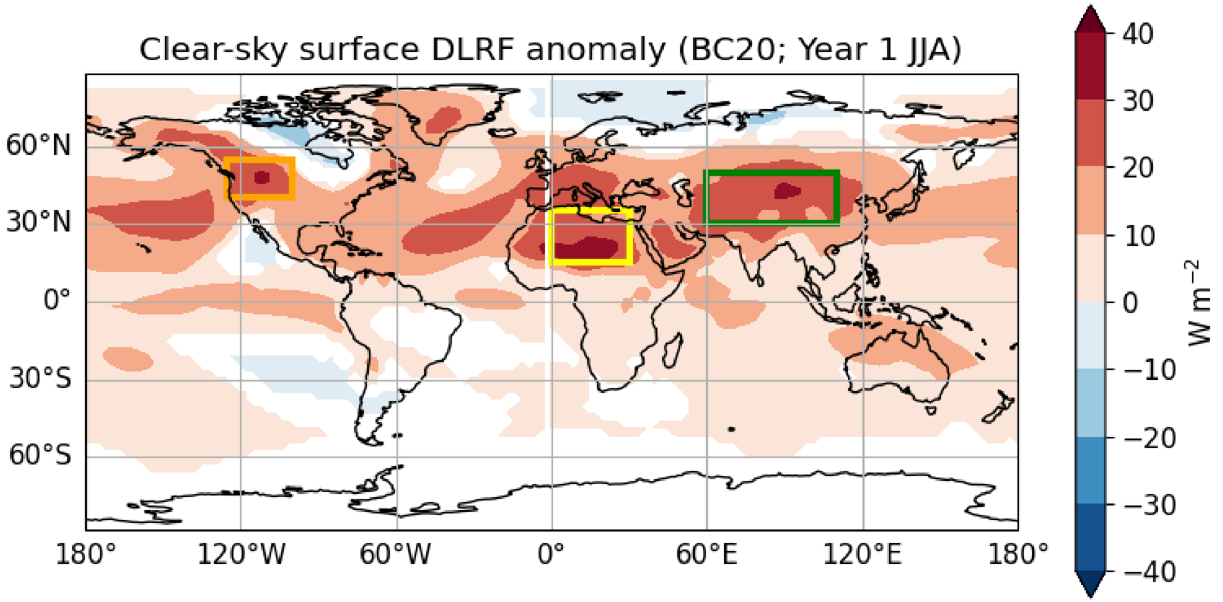

Figure R3. Response of clear-sky surface DLRF for BC20 in the first JJA. It is defined as positive downward. White patches indicate changes that are not significant at 95% confidence level using a t test.

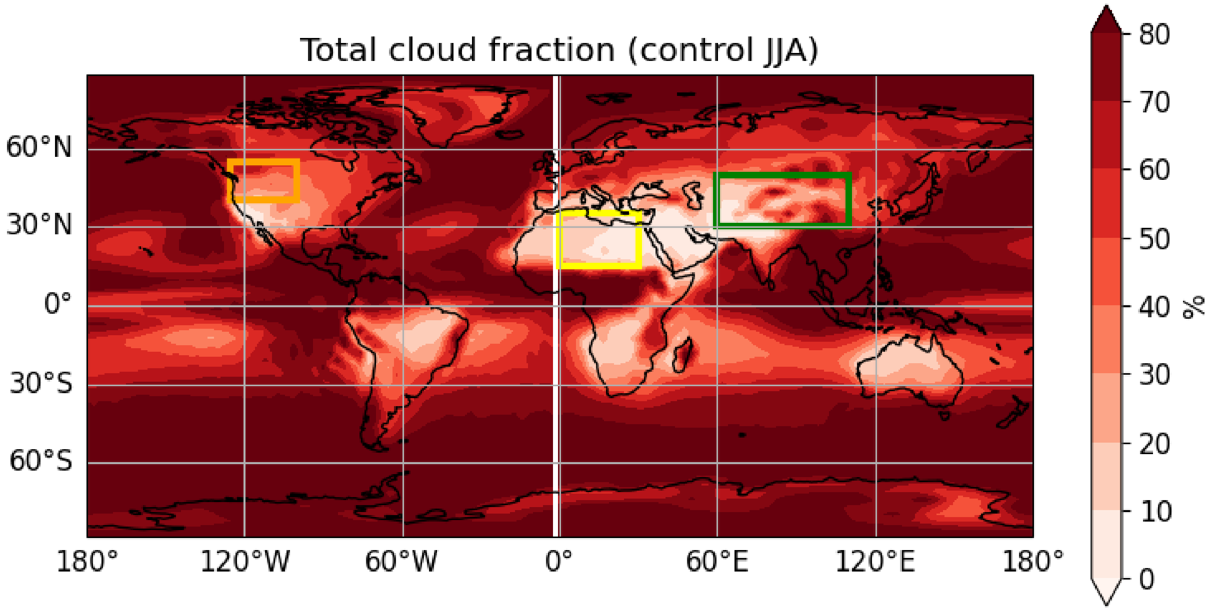

Figure R4. Total cloud fraction in JJA of the control simulations.

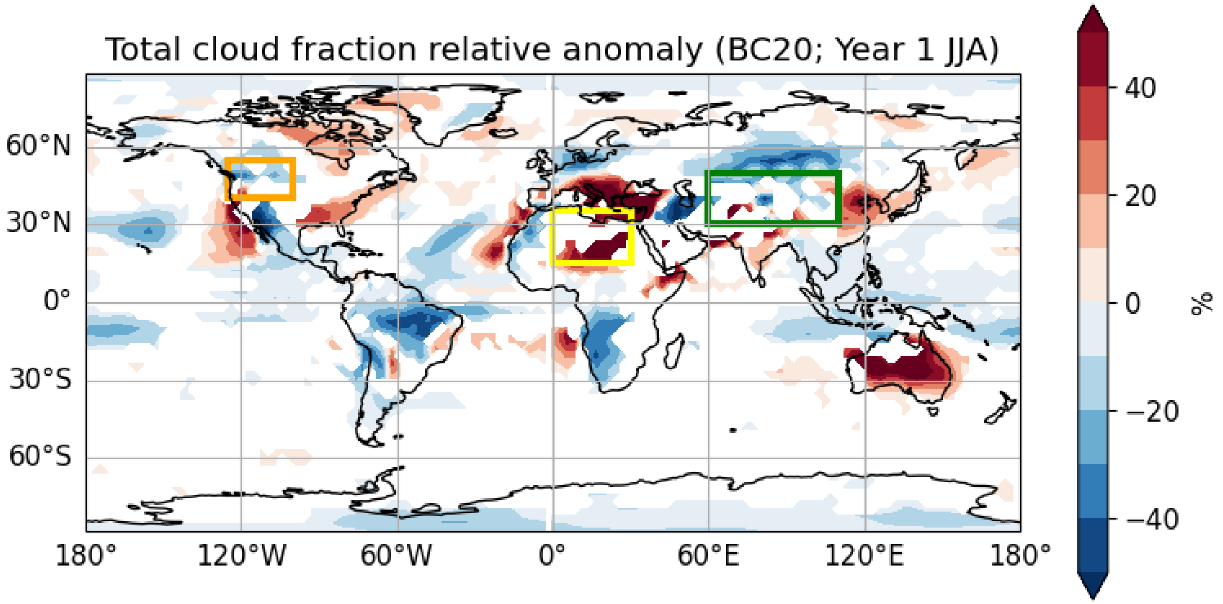

Figure R5. Percentage change of total cloud fraction in JJA of the first year for BC20. White patches indicate changes that are not significant at 95% confidence level using a t test.

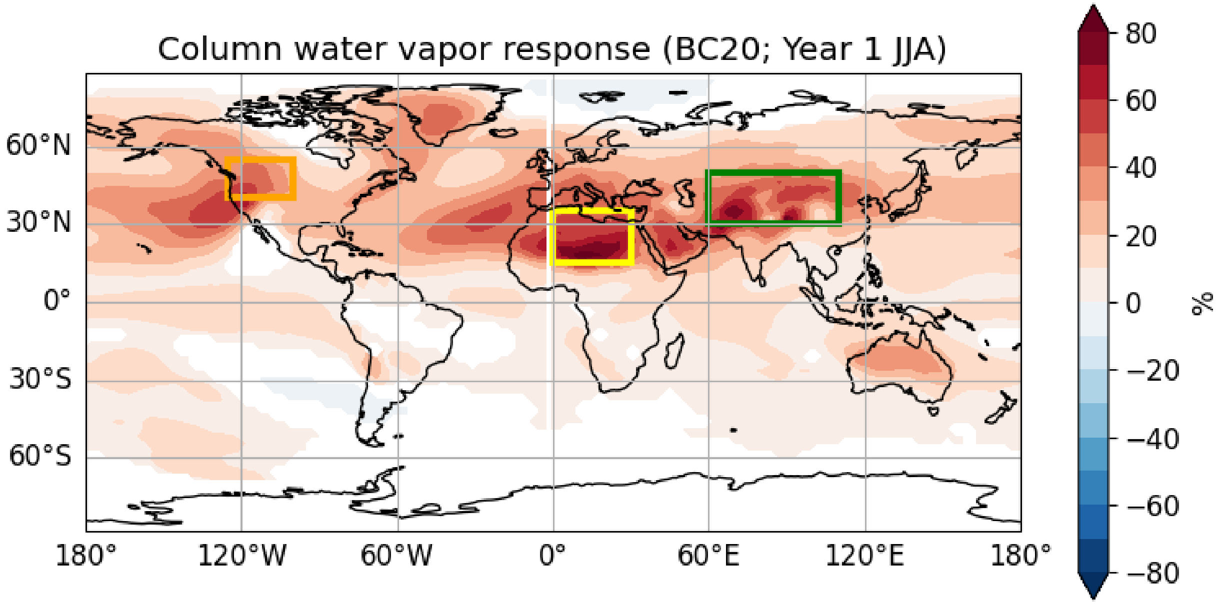

Figure R6. Response of column water vapor in JJA of the first year for BC20. White patches indicate changes that are not significant at 95% confidence level using a t test.

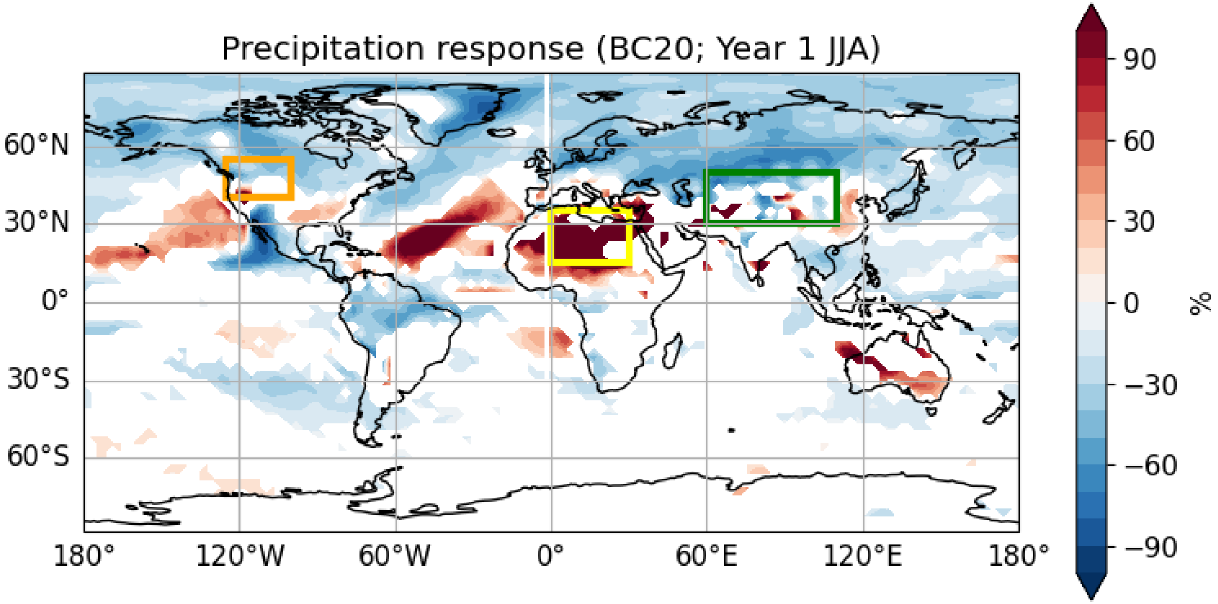

Figure R7. Response of precipitation in JJA of the first year for BC20. White patches indicate changes that are not significant at 95% confidence level using a t test.

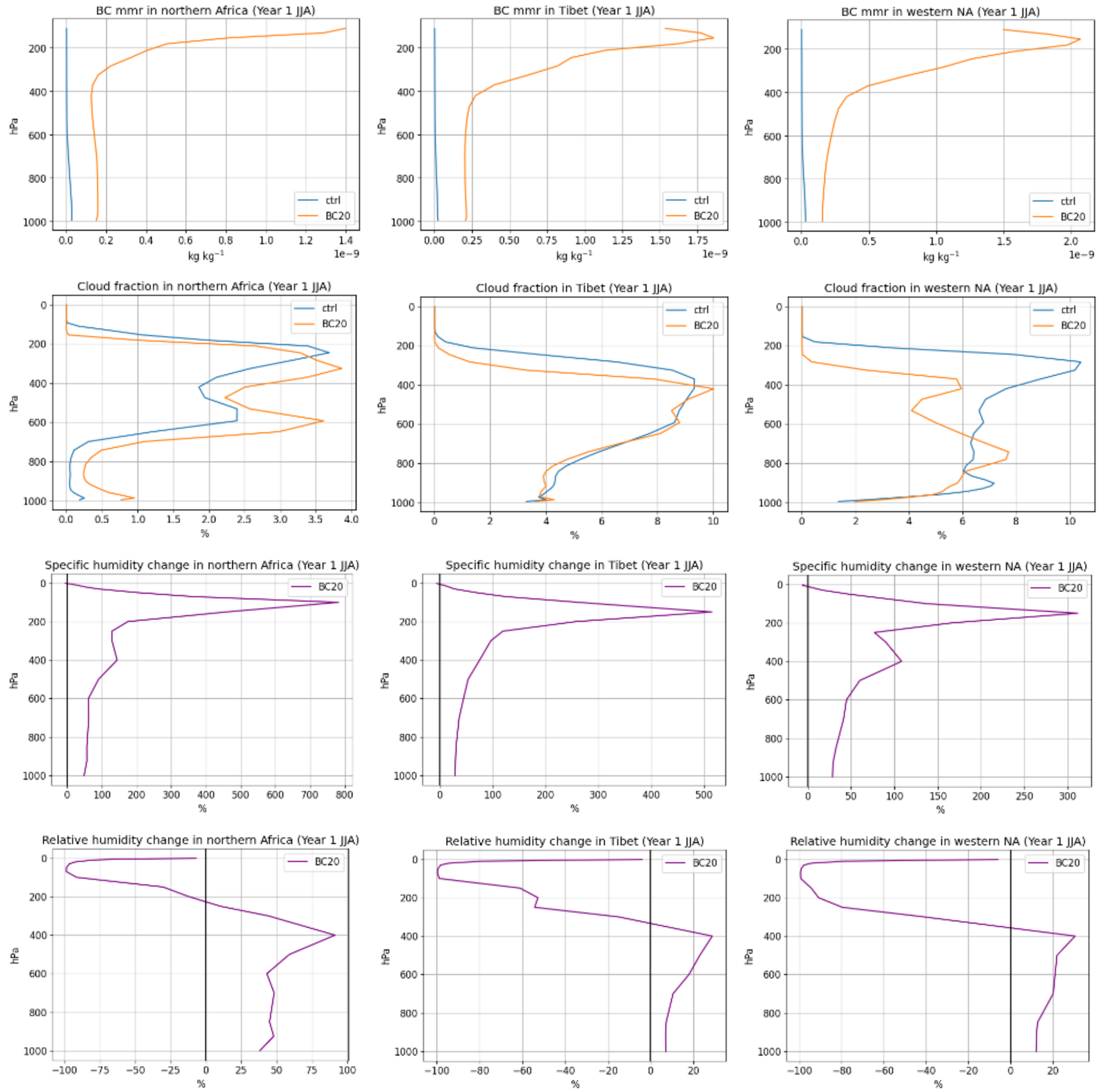

Figure R8. Vertical distributions of the BC mass mixing ratio, cloud fraction, specific humidity change, and relative humidity change over the regions that experience surface warming in the first JJA. The areas of northern Africa (left column), Tibet (middle column), and western North America (right column) correspond to the yellow, green, and orange boxes in Fig. R1, respectively.

Why does the paper choose the BC injections that they did? They call for model intercomparison studies, but do not use the same injection scenarios as other studies. It seems they are not aware of Toon et al. (2019) which examined scenarios with the same *range as this paper, 5 Tg, 15 Tg, 27 Tg, and 37 Tg. This paper should have used the same ones so they could be compared.*

Toon, Owen B., Charles G. Bardeen, Alan Robock, Lili Xia, Hans Kristensen, Matthew McKinzie, R. J. Peterson, Cheryl Harrison, Nicole S. Lovenduski, and Richard P. Turco, 2019: Rapid expansion of nuclear arsenals by Pakistan and India portends regional and global catastrophe. *Science Advances*, **5**, eaay5478, doi:10.1126/sciadv.aay5478.

- ⇒ We appreciate this important point. We chose the BC injections that we did since Turco et al. (1990) estimated 20 Tg to be the lower bound of the plausible range of BC surface emissions for the full-scale nuclear exchange scenario, as mentioned in the Introduction. The BC injections of this size are extremely large compared to climatological BC burden and could cause unprecedented climate impacts, albeit relatively smaller than 150 Tg, the mean of the estimated range.
- ⇒ Our focus here is the lower-end US-Russia exchange scenario motivated by Turco et al. (1990), whereas Toon et al. (2019) examines India-Pakistan exchange scenarios. We now clarify this distinction more explicitly in the revised Introduction and Discussions.
- ⇒ Our suggestion for intercomparison is motivated by how this relatively underexplored regime, from a hypothetical limited nuclear exchange, leads to strong, disruptive, and unexpected transient impacts. We believe this would be valuable to check in other models.

They also should be aware of Oman et al. (2006). They found summer warming over Africa and Asia after a volcanic eruption, and the explanation was a weaker summer monsoon, which produced fewer clouds. This paper needs to show the distribution and anomalies of clouds and precipitation in the first JJA, and diagnose whether the response they found was due to a dynamic response, or simply an evaporation of the clouds due to upper troposphere heating.

Oman, Luke, Alan Robock, Georgiy L. Stenchikov, and Thorvaldur Thordarson, 2006: High-latitude eruptions cast shadow over the African monsoon and the flow of the Nile. *Geophys. Res. Lett.*, **33**, L18711, doi:10.1029/2006GL027665.

⇒ Thank you for the suggestion. Our assessment of the role of clouds and water vapor has been discussed above and has determined that a clear-sky effect is common for all the regions while the cloud response does not provide a simple explanation. For example, in our model simulations, cloud fraction increases over the region of northern Africa that experiences warming in the first JJA (Fig. R5), so the suggested effect should not be relevant. The surface DLRF increase is likely more associated with water vapor feedback, as suggested above.

The BC lifetime in this simulation is much shorter than in previous work. This has to be explained, with figures showing the BC distribution vertically. What was not washed out immediately should have been transported to the upper stratosphere and lasted for years. Previous work had e-fording lifetimes of 5-7 years. Why is it so short here?

⇒ Our reported findings of BC lifetimes are not very different from previous work. From previous work, the reported stratospheric BC mass e-folding time ranges from 2-8 years based on the previous literature we cited in the original manuscript (Coupe et al., 2019; Mills et al., 2014; Pausata et al., 2016; Robock et al., 2007a, 2007b; Wagman et al., 2020; see their full citations in original manuscript). The stratospheric BC mass e-folding time found in our simulations ranges from 3-4 years, which falls within previous reported values. While it is at the short end of the range, we believe that it is reasonable, given the limitation that CanESM5.1 is a low top model. While the BC lofting effect is present in the model, it may be limited. As stated above, we have included vertical distributions of BC in Fig. R8. We will include them in the Appendix and refer to them in the text.

The terminology of "low-moderate" injections, "standard high-end cases," and "relatively weak" injection needs to be changed. There is no standard case, and all incidents of nuclear war, including 5 Tg injections would be horrific, and would not be low or moderate.

⇒ We agree that all incidents of nuclear war would be horrific. Indeed, this is what motivated us to study the impacts of what would be even a limited nuclear exchange, compared to the available arsenal, between these two states. But the term "low-to-moderate" inadvertently connotes a lack of harm; that was not our intention. In our revision, we will replace this terminology with a quantitative indicator.

The caption for Fig. 4 says sea ice is shown by orange lines, but I don't see any.

⇒ Thank you for catching this. In Line 249-250 "The solid and dashed orange lines indicate the sea ice lines for the scenario and for the climatology, respectively. It is defined as the grids with 15% sea ice area." should belong to the caption of Fig. 5. We will change this in our revision.

There are 23 additional comments on the attached annotated manuscript which also should be addressed.

For Line 1, 12, 14, 56, 64:

⇒ These are related to the comment on the use of the terminologies above. In our revision, we will replace this terminology with a quantitative description where possible.

For Line 27, 28

⇒ We will include the suggested literature, which are relevant and recent.

For Line 50, 72, 331

⇒ These are related to the comment on the choice of the BC injections, which has been replied above.

For Line 143

⇒ The first half of the comment is regarding stratospheric BC lifetime and has been replied above. As for the second half of the comment on the use of CanESM5 for studying the Mt. Pinatubo volcanic eruption, we note that CanESM5 has not been used to actively simulate stratospheric aerosols from the Mt. Pinatubo eruption although it has been used to study the climate response to the radiative forcing from the eruption, for example in Pauling et al. (2023) and Rieger et al. (2020).

Pauling, A. G., Bitz, C. M., and Armour, K. C., 2023: The climate response to the Mt. Pinatubo eruption does not constrain climate sensitivity. *Geophysical Research Letters*, **50**, https://doi.org/10.1029/2023GL102946.

Rieger, L. A., Cole, J. N. S., Fyfe, J. C., Po-Chedley, S., Cameron-Smith, P. J., Durack, P. J., Gillett, N. P., and Tang, Q., 2020: Quantifying CanESM5 and EAMv1 sensitivities to Mt. Pinatubo volcanic forcing for the CMIP6 historical experiment. *Geosci. Model Dev.*, **13**, 4831–4843, https://doi.org/10.5194/gmd-13-4831-2020.

For Line 176, 177

⇒ Thank you for the corrections. In our revision, we will place caption on the same page of the table and replace “brackets” with “parentheses”.

For Line 235

⇒ This is related to the first comment above and has been replied.

For Line 249

⇒ This is related to the question about the orange lines and has been answered above. Thank you again for catching this.

For Line 270

⇒ “Following the fire” was referring to following the fire emission. We will replace it by “following the fire emission”.

For Line 310, 311

⇒ As suggested above, in our revision, we will include the vertical distributions of BC mass mixing ratio, cloud fraction, specific humidity, and relative humidity in the

Appendix. We will also add relevant discussion on water vapor feedback in Discussions and Conclusions.

For Line 409

⇒ We will use standard Copernicus formatting in the revised text.

For Line 490, 493

⇒ We will specify 2007a and 2007b for the two references.