Author Response to Reviewer 2

We thank the reviewer for her/his thoughtful and detailed comments, which helped improve this manuscript. Please note: Reviewer's comments are listed in blue fonts. And responses are italicized text below each reviewer's comments.

This manuscript describes an optimization method to improve the calibration of adjustable parameters in global climate models. This works builds upon previous works by Zhang et al. (2015, 2018). The main difference is the addition of a global constraint to enforce that the net energy imbalance at TOA be less than 1 W/m2. This constraint is incorporated by simply adding a penalty term to the cost function (Eq. 6). When applied to CAM5.3, the proposed method results in a modest overall improvement of 6.3% in the cost function. Among the fields subject to optimization (LWCF, SWCF, PRECT, Q850, T850), the largest improvements occur for SWCF, Q850, with minor improvement for T850 and minor degradations for LWCF and PRECT (Table 4). Since CAM5.3 is already a well-tuned model, it is not particularly surprising the overall improvement is small.
Overall, the manuscript is clear and easy to read and fits well within the scope of GMD.
I would recommend publication after some modifications to further improve it.
Thank you very much for your recognition. We also appreciate your following comments and suggestions.

1. It should be noted that the idea of including a constraint on the global value of net radiation is not new. From Jackson et al. 2008 (J Climate): "We also included a term constraining the global net radiative balance at the top of the atmosphere. We had intended to give this a target of 0.3 W m−2".
Reply: Thank you for the recommended paper. In this paper, the simulation skills of "Net longwave top", "Net shortwave top" and other variables are added to the cost function. Our paper presents the optimization algorithm to strengthen radiation balance as a strong constraint. Meanwhile, other variables are optimized as much as possible if the constraint is met. Of course, both methods are the ideas to the problem, and the papers you recommend also give us some possible directions for future work.

2. Figure 2 and corresponding text. There is a clear separation between optimized results with and without constraint. This is interesting and warrants further discussion.
How different are the unconstrained optimized simulations compared to the constrained ones? This could be illustrated by showing a few selected figures. Also, the constraint is applied as a rather brutal all-or-nothing penalty function that may prevent a wider exploration of the parameter space. One wonders whether a smoother penalty function for the global net radiation have led to different (better) constrained solutions? I would recommend exploring alternate formulations for the penalty function (for example quadratic or exponential) to check whether the specific formulation of the penalty function has any impact on the results.
Reply: Nice insight! The reasons why the points of constrained optimization and unconstrained optimization are separated in Figure 2 as follows: The first reason is that we only selected the

top 15 optimization results for display. The other points in the tuning process are not so distinct. The second reason is the starting points for optimization we chose leads to the current results in Figure 2. If we use different starting points, the optimization results may be different. The third reason may be also related to your second point. Since we use radiation balance as a particularly strong constraint here, the exploration space in the tuning process tends to be in the space which obeys the constraint. Compared with the unconstrained optimization algorithm, the searching path for optimization of our algorithm is different.

You mentioned that the choice of smooth constraints will also have a great impact on the search space, and whether the final optimization results is better or not need to be evaluated carefully. Anyway, it is a very good idea! Sorry, due to the long running time of the AMIP experiment, we can't immediately give the corresponding experimental results. In addition, your proposed quadratic and index constraint forms give us a lot of inspiration. In the future work, we are also about to carry out corresponding experiments.

3. Table 1 and corresponding text. Under constrained optimization, the final value for 3 out of 6 parameters hit the lowest allowable limit. This should be discussed.

Reply: Thanks for pointing this out! Indeed, three parameters (zmconv_c0_lnd, zmconv_c0_ocn, zmconv_tau) hit the lowest allowable limit.

In CTL experiment, the net TOA imbalance is around 0.6 W/m2, and the incoming shortwave radiation is larger than the outgoing longwave radiation. First, we found that TOA LW radiation and LWCF cannot reach the better performance at the same time, due to the bias in clear-sky longwave radiation flux (FLNTC). So, the radiation balance is a strict constraint, and the performance of LWCF has to be sacrificed. This is revealed by the degraded LWCF performance (1.072) as in Table 4. Second, in the tuning process, we found that shortwave radiation flux is more sensitive to the tuning parameters than longwave radiation flux. To reach a strict small TOA imbalance, the easier tuning direction is to reduce the incoming shortwave radiative flux and to get closer to the outgoing LW radiation flux. Indeed, the final constrained tuning result gets a small TOA imbalance (0.1 W/m2) with TOA shortwave and longwave radiation flux 236.47 W/m2 and 236.37 W/m2, respectively. Three parameters hitting the lowest allowable limit all are used to reduce the incoming shortwave radiation flux largely. To get the final TOA balance and keep an acceptable model performance, the picked tuning parameters here has to hit the lowest limit. It also suggests the difficulty to get perfect performance in all perspectives.

We try to discuss this in Section "Interpretation of the results" (Page 7 Line 26-Page 8 Line 2) of our revised version.

4. Page 1, lines 17-18: rephrase to make it clear that the constraint is abs(FLNT-FSNT) < 1.

Reply: Thanks for pointing this out. The sentence in lines 17-18 has been revised to "The radiation constraint is defined as the absolute difference between the net longwave flux at top of model (FLNT) and the net solar flux at top of model (FSNT) less than 1 W m-2."

5. Page 1, line 20: "under the premise of a profound understanding": delete. I don't see any new "profound understanding" emerging from this work or method.

Reply: The sentence has been deleted.

6. Page 1, line 25: "may result in breaking physical mechanisms that models have to address": delete or clarify what is meant by this (i.e. be specific, not vague).

Reply: Thanks. We have deleted the sentence "and may result in breaking physical mechanisms that models have to address."

7. Page 2, line 13: "by using" → "using"

Reply: Corrected

8. Page 3, line 5: "extreme": delete

Reply: Deleted.

9. Page 3, lines 10-11: "Qian et al. (2015) indicated that some parameters in cloud microphysics and convection are very sensitive to net radiation flux": isn't this the other way around? Net radiation flux is very sensitive to cloud microphysics and convection parameters.

Reply: Sorry, this is a mistake. We have modified this sentence to "Net radiation flux is very sensitive to cloud microphysics and convection parameters (Qian et al.2015)."

10. Page 7, line 1: "The CNTL experiment has excelled in simulating the spatial distribution of SWCF (Fig. 5c)". With RMSE between 14 and 15 W/m2, neither EXP nor CNTL can realistically be described as excelling in representing SWCF. These are much larger errors than seen in recent CMIP6 models.

*Reply: Thanks for pointing this out. The model we used in this work is CAM5.3 with a resolution of 1.9*2.5, which is different from the atmospheric component of the latest CMIP6 model CESM2. And the resolution is also different. The CESM model of CMIP6 is better than the CESM model used in CMIP5, especially for the simulation results of SWCF. As reported, the CMIP6 model have greatly improved the simulation of SWCF (The global average RMSE is reduced by approximately 5W/m2). However, as we worked on this, the CMIP6 model has not yet been released publicly and we cannot use this improved version to evaluate our tuning algorithm. But we believe that we can also get better performance for the latest model version while keeping the radiation balance. We will try to use the latest model version to the following work.*