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An effective parameter optimization with radiation balance constraint in CAM5

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1. Abstract

Uncertain parameters in physical parameterizations of General Circulation Models (GCMs) greatly impact model performance. Traditional parameter tuning methods are mostly unconstrained optimization, leading to the simulation results with optimal parameters that may not meet other conditions that models have to keep. In this study, the radiation balance constraint is taken as an example, and is involved in the automatic parameter calibration procedure for earth system model. A new method , which combines the external penalty function method and the simplex downhill algorithm , is used to solve this global optimization problem with constraints. In our experiment, we use CAM5 5-yr AMIP simulation forced with prescribed seasonal climatology of SST and sea ice. We consider the synthesized metrics using global means of radiation, precipitation, relative humidity, and temperature as the goal of model tuning, and simultaneously keep the condition that upwelling longwave flux at top of model (FLUT) and net solar flux at top of atmosphere (FSNTOA) achieve better balance. Experiment results show that the synthesized metrics is 5.03% better than the control run. At the same time , the radiation imbalance has been improved with respect to the result of the default experiment by 4.77%. In addition, through iterative tuning, we find a see-saw effect between longwave cloud forcing (LWCF) and FLUT in our CAM5 simulations, which means that if the LWCF simulation results improve, the FLUT simulation value will get worse, and vice versa. As a result, if we want to reach the target that FLUT,LWCF and FSNTOA are all close to the observations in CAM5, we have to first improve the simulation of the clear sky upwelling longwave flux at top of model (FLUTC).

2. Problem to solve

The automatic parameter calibration method can improve the overall performance of the climate model[1]. However, simply following the widely-used global optimization algorithms, the optimal parameters found may not meet the requirements of certain physical constraints.

For example, improving the overall performance of the model, we also hope that the model will always keep the radiation balance at the top of atmosphere[2], which is an important indicator of the quality of the model. So how to conduct an automated and efficient parameter calibration algorithm for current earth system models to solve the constrained problem is critical, which is still not well investigated.

3. A new method

In order to meet the physical requirements and optimize the overall performance of the climate model, we propose a constrained optimization algorithm.

Assuming the metrics to be adjusted is f (x), the inequality constraint is q (x), and the equality constraint is h (x), then the constrained optimization problem can be represented by the following formulas.

$$\begin{aligned} &\min f(x), x \in R^n \\ \text{s.t. } & q_i(x) \geq 0, i = 1,2,\dots,m \\ & h_j(x) = 0, j = 1,2,\dots,r \end{aligned} \qquad (1)$$

First of all, we take the penalty method of extrapolation to reformulate the constrained problem into an unconstrained problem.

$$F(x) = f(x) + \sum_m \lambda_i q_i(x) + \sum_r \beta_j h_j(x) \qquad (2)$$

Then we use the improved simplex downhill algorithm[1] to iteratively optimize the augmented function F(x).

The first step

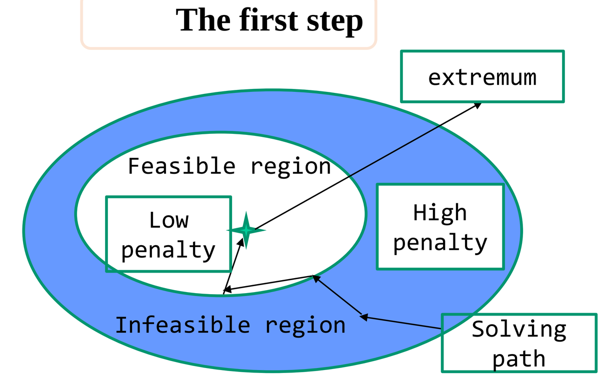


Fig 1. External penalty function method

The second step

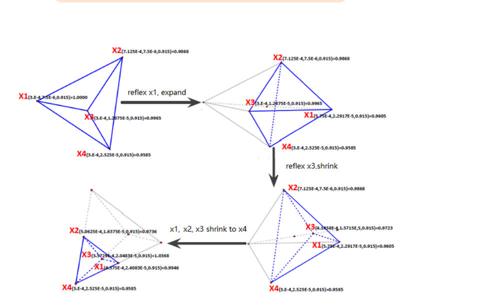


Fig 2. Simplex downhill algorithm

4. Study Case

In order to verify that we can tune the climate model with the proposed algorithm for constrained problems, we design the following experiments.

After converting the constrained problem into unconstrained problem, we do simplex downhill method for the augment function. Each iteration is a 5-year AMIP simulation with a resolution of 2 degrees from 2000 to 2004 in CAM5, and the output of the climatology in last three simulated years is used to calculate synthesized metrics and constraint.

We find that the radiation imbalance is still about 2.67W/m² in the default experiment, whose parameter values are from the model configuration for CMIP5 experiments, and they are recommend by climate experts. The optimization effects in our experiments are relative to the default experiment.

The synthesized metrics we use to evaluate the model performance are shown as χ^2 in the following formula. It indicates an overall improvement of the performance of the tuned simulation relative to the control run based on a number of model outputs (Table2). The smaller this value, the better the improvement is.

$$(\sigma_m^F)^2 = \sum_{i=1}^{I} w(i)(x_m^F(i) - x_o^F(i))^2 \qquad (3)$$

$$(\sigma_r^F)^2 = \sum_{i=1}^{I} w(i)(x_r^F(i) - x_o^F(i))^2 \qquad (4)$$

$$\chi^2 = \frac{1}{N^F} \sum_{F=1}^{N^F} \left(\frac{\sigma_m^F}{\sigma_r^F}\right)^2 \qquad (5)$$

$x_m^F(i)$ is the model outputs, and $x_o^F(i)$ is the corresponding observation or reanalysis data. $x_r^F(i)$ is model outputs from the control simulation using the default values for the parameters in Table 1. ω is the weight due to the different grid area on a regular latitude–longitude grid on the sphere. I is the total grid number in model. N^F is the number of the chosen variables.

Coupled with the radiation balance constraint, the optimization problem of this study can be expressed as above formula,

$$\begin{aligned} &\min \chi^2 \\ s.t. \ & \frac{ABS(FSNTOA_m - FLUT_m)}{ABS(FSNTOA_r - FLUT_r)} - 1 < 0 \end{aligned} \qquad (6)$$

Table 1. Parameters to be adjusted

Parameter	Range	Default
zmconv_c0_lnd	2.95e-3 ~ 8.85e-3	5.9e-3
zmconv_c0_ocn	0.0225 ~ 0.0675	0.045
zmconv_tau	1800 ~ 5400	3600
cldfrc_rhminh	0.6 ~ 0.9	0.8
cldfrc_rhminl	0.8 ~ 0.95	0.8975
cldsed_ai	300 ~ 1100	700

Table 2. Output variables

Output	Variable	Full Name	OBS
metrics variables	LWCF	Longwave cloud forcing	CERES-EBAF
	SWCF	Shortwave cloud forcing	CERES-EBAF
	PRECT	Total precipitation rate	GPCP
	Q850	Specific Humidity at 850hPa	MERRA
	T850	Temperature at 850hPa	MERRA
constraints variables	FLUT	Upwelling longwave flux at top of model	CERES-EBAF
	FSNTOA	Net solar flux at top of atmosphere	CERES-EBAF

5. Results

After 28 rounds of tuning iterations, we find that a set of parameters can make the synthesized metrics value reduced by 5.03%, and the gap between FLUT and FSNTOA is smaller than the default experiment. Please find detail results in Table 3 and Figure 3，4 and 5.

Table 3. The smallest metrics in feasible solution

	DEF	OPT
synthesized metrics	1	0.949679
ABS(FLUT-FSNTOA)	2.6647	2.5377

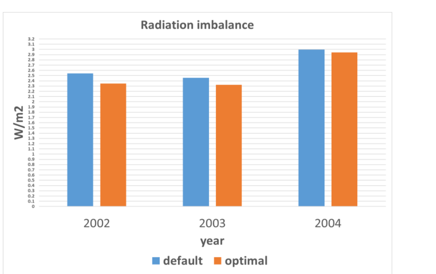
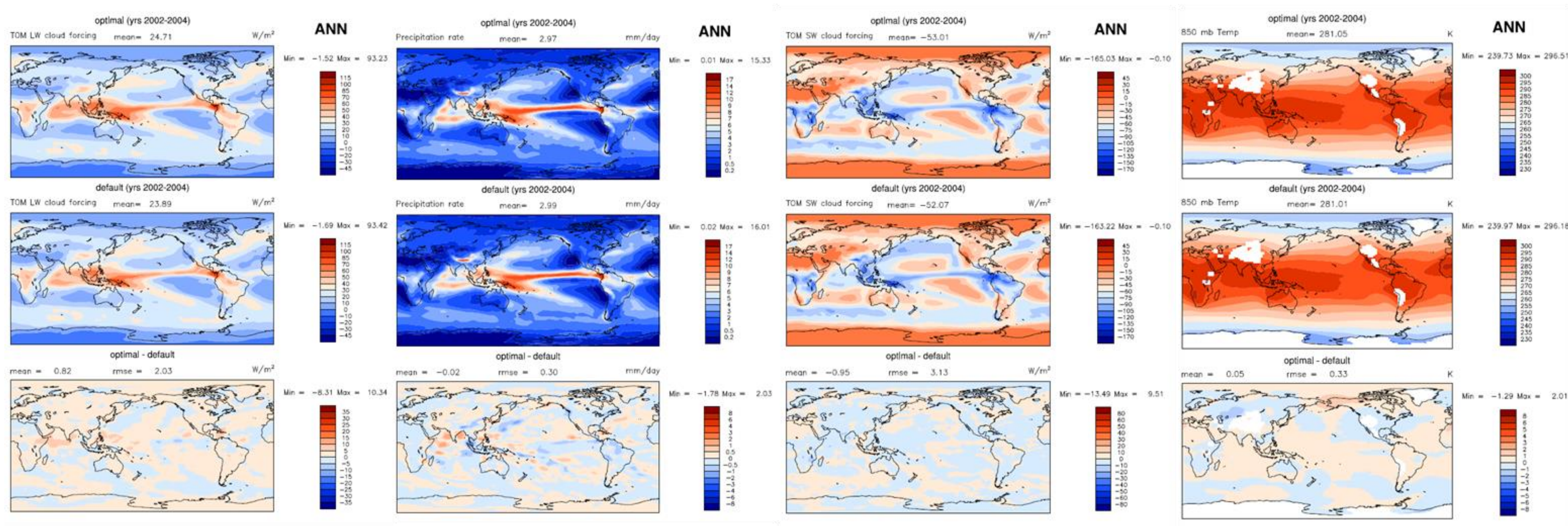


Fig 3. Radiation bias in optimization and Default simulation



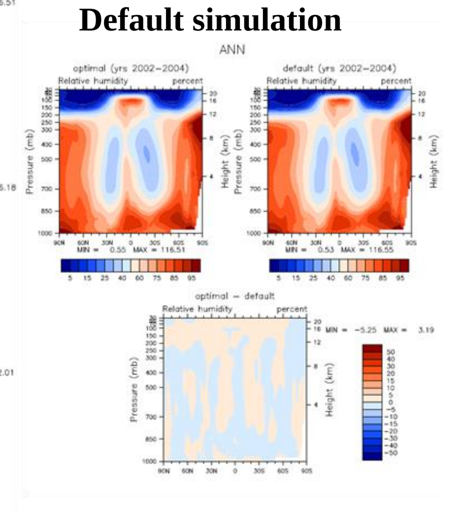


Fig 4. Detail comparison of different output variables between the simulation with optimal parameters and control run.

As we can see, in the optimized results, the performance of LWCF and PRECT are improved relative to the default experiment. And the Q850, T850 and SWCF are all near the default values. Further analysis and evaluation are still under investigation.

For the constraints, we find that the average radiation bias with the optimal parameters in the last three years is 4.77% better than the default experiment.

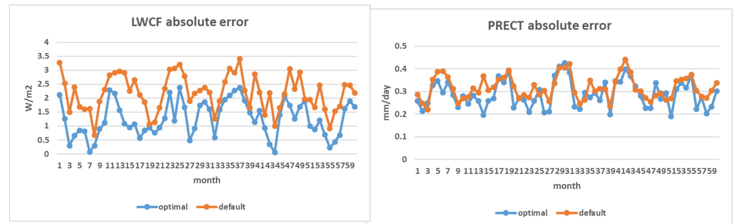


Fig 5. The comparison on LWCF and PERCT between the simulation with the optimal parameters and control run

6. Discussion

Although the problem of radiation balance has been improved, both FLUT and FSNTOA have a certain distance from the observations. In the tuning process, it is obvious that there is a see-saw effect between LWCF and FLUT. which means that if the LWCF simulation results are improved, the FLUT simulation value will get worse, and vice versa. Therefore, the simulation results of LWCF and FLUT can not be improved at the same time.

In order to understand why the seesaw effect exists, we also compare the simulated and observed values of FLUTC, according to the formula LWCF=FLUTC-FLUT in CAM5 (also in most of atmosphere models). We find that FLUTC simulation results are always about 5W/m² less than the observations as shown in Figure 7.

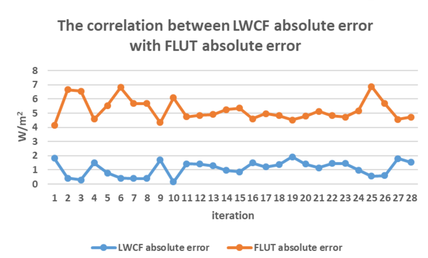


Fig 6. The seesaw effect of LWCF and FLUT

Fig 8. The results of single parameter perturbation sampling

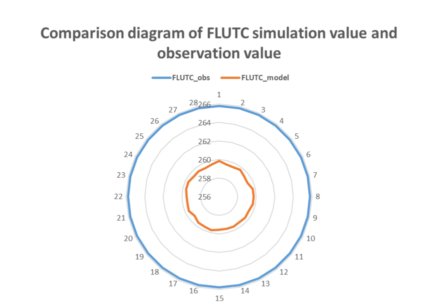


Fig 7. The gap between the simulation results and the observations of FLUTC

To further confirm the above phenomenon, we perturb each of the parameters with a single parameter perturbation sampling method to do a month's simulation in CAM5. Although the result of each parameter is not exactly the same, the see-saw effect can still be seen.

In addition, we change the constraint condition to minimize the difference between the simulated and observed values of FLUT and FSNTOA. The same effect still exists even with more optimization iterations (50 iterations in our experiments).

As a result, if we want to reach the target that FLUT and FSNTOA are close to the observations in CAM5 while the applied metric is minimized, we have to first improve the simulation of the FLUTC.

7. Conclusions

- The constrained optimization algorithm for earth system models is proposed in this study, which can help model developers and users to find good parameter configurations for better model performance while keeping satisfying the physical constraints.
- The see-saw effect exists between longwave cloud forcing and upwelling longwave flux at top of model in our experiments, which hinders the model to reach the target of the simulated radiation results to be all close to the observations in CAM5. In order to completely solve this problem, we need to improve the design of physical parameterizations of the model beyond parameter tuning.

8. References

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