Final Report

EXPANDING THE COMPUTATIONAL FRONTIER OF MULTI-SCALE ATMOSPHERIC SIMULATION TO ADVANCE UNDERSTANDING OF LOW CLOUD / CLIMATE FEEDBACKS

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Effort in parallelizing the ultra-parameterization (UP) using Open-MP

The co-PI, in coordination with the Lead-PI (Prof. Pritchard) has been engaged in the effort to parallelize the cloud-resolving model, SAM, used as the UP in UP-CAM using the multithreading approach provided by the OpenMP protocol. The general strategy in parallelization the UP-CAM follows the one used in SP-CAM, which was developed by the co-PI. In both SP-CAM and UP-CAM, the CRM is inserted in each column of the host GCM, CAM, and parallelization is achieved by running a scalar version of each CRM in parallel using MPI. Ideally, and this has been implanted for the first time in UP-CAM, each CRM would be run on individual core. In this case, the maximum number of cores that the UP-CAM can use is the total number of GCM grid columns. Further acceleration would follow two different approaches (beyond GPU acceleration): to use the MPI within each CRM and use multithreading provided by OpenMP, that is further parallelize the internal loops in CRM using compiler directives. The first approach is quite complicated to implement in UP-CAM, so the co-PI has been focusing on the second approach.

The first step that co-PI has made was to identify possible bottlenecks in computation flow in CRM. The CRM has been run in offline mode using the target UP-CAM configuration, that is the 2D domain of 128x120 grid cell, horizontal grid spacing 250 m and time step 2 s, Morrison2005 two-moment microphysics, and RRTM radiation. The tests revealed microphysics was the most expensive part of the code (57%) followed by the advection of scalars (14%). Further experiments by the co-PI applying OpenMP directives to these bottlenecks have revealed that the sweet spot is 4 cores, which gives 54% relative speedup efficiency or speedup of 2.2. Conceptually, by parallelizing other loops, the efficiency could be increased further to 60%, which is not very different from the efficiency of 70% of pure MPI using 4 cores. Therefore, generally, it has been demonstrated that the OpenMP strategy can indeed be, in principle, made nearly as efficient as the MPI strategy to parallelizing the CRM in UP-CAM, with OpenMP strategy being much simpler in implementation as it does not involve any code changes beyond insertion of simple compiler directives. Despite this promise, the OpenMP strategy has not been eventually implemented in the UP-CAM, due to some technical difficulties; for example, relatively large spinup cost of invocation of Open-MP threads on the target computer architecture.

Effort in tuning the UP-CAM

The co-PI has also been involved in the process of tuning the UP-CAM to improve the simulation of boundary-layer clouds. The co-PI has been working with the UCI Team on various ways to change the cloud radiative forcing by changing microphysical parameters and subgrid-scale closure using his experience with tuning the SP-CAM. The procedure is described in the paper by Parishani et al (2018).

Dynamical horizontal grid-spacing of super-parameterization in SP-CAM as alternative to mini-LES approach

One of the weaknesses of the conventional super-parameterization (SP) approach is relatively coarse grid spacing, typically 4 km. While such a grid spacing is quite adequate for deep convective clouds, it is certainly not sufficient for resolving shallow convection, especially boundary layer clouds. One of the primary motivations for the UP approach in this DOE project has been to bridge that gap by "brute force", that is using high-resolution of just a few hundred meters to represent both deep and shallow simultaneously, which, of course, means high computational cost.

The alternative approach with much smaller computational cost would be to use a so-called mini-LES, the concept of which this co-PI proposed a few years ago. The proposal for this project explicitly includes this approach to be explored by this co-PI using his general expertise in SP approach. The initial idea was to incorporate a second super-parameterization to be used exclusively to resolve boundary-layer clouds, referred to as a mini-LES, which would run in parallel to a primary conventional SP. That is, the SP would handle deep convection with "normal" grid-spacing 4 km as before, while the mini-LES would run in parallel only representing shallow boundary-layer clouds with resolution 250 m. The proposal for this project contains some preliminary results of such approach applied to SP-CAM and showed some promise as it improved the low-cloud amount climatology of SP-CAM compared to observations. However, there have been some conceptual difficulties and inconsistencies of the approach that needed to be addressed by this project. For example, the combining the low-cloud fields, such as cloud water and cloud fraction, produced by both SP and mini-LES for radiation computations has proved to be a major challenge. Also, there has been a concern of "double counting" of subgrid-scale vertical enthalpy fluxes calculated by both SP and mini-LES. Also, quite often, the convection in mini-LES would try to go deep, which, taking into account the domain size of just a few km, would be problematic. No plausible and "clean" solution has been found to those difficult problems over the coarse of the project.

Instead, while working on various modes of mini-LES approach, the co-PI has realized that there is an alternative approach to running SP and mini-LES in tandem in SP-CAM that would easily solve the aforementioned difficulties. In this new approach, only one SP would still be run, like in "classical" SP approach, but the horizontal resolution of SP would be dynamically changed, so that it would run at coarse resolution over regions of deep convection and fine-resolution over regions of predominantly shallow-convection, while maintaining the number of horizontal grid cells. Of course, it would not be prudent to assign those regions manually as there are many regions with intermittent deep and shallow convection, so the new SP should dynamically and automatically adjust the horizontal grid spacing, depending on the presence of deep convection. Of course, it should not be a simple on-off switch as it would produce computational shocks from abrupt change of resolution that could destabilize the simulation or even crash it.

After several failed attempts and deliberations with the other members of the UP-CAM project team, a working prototype of the approach has been developed and implemented by co-PI in SP-CAM. The approach uses the vertical velocity at 2000 m as an indicator of deep convection. Briefly, the approach is as follows.

The horizontal grid spacing Δx of the SP is evolving in time and is computed on a SP time step n+1 using it's value on the previous time step n as

$$\Delta x^{n+1} = \Delta x^{n} - \Delta t\left(\frac{\Delta x^{n} - \Delta x_{shel}}{\tau_{shel}} + \delta\frac{\Delta x^{n} - \Delta x_{deep}}{\tau_{deep}}\right) \qquad (1)$$

where Δx_{shel} =250m and Δx_{deep} = 4000m are the grid-spacing for shallow and deep convection regimes, respectively, with corresponding nudging or relaxation time scales τ_{shel}=1800s and τ_{deep}=3Δt, where Δt is the SP time-step (usually 10-20 s). The switch parameter δ =1 when deep convection is present and δ=0 otherwise. The deep convection is present when there is any cloudy grid cell (cloud water/ice is in access of 0.1 g/kg) in the SP domain above 2000m (that is above most boundary layers' top) where $w^{n}\Delta x^{n} > w_{deep}\Delta x_{shel}$, where w_{deep}= 4 m/s. After a new horizontal grid spacing is set, the vertical velocity in the domain needs to be adjusted as $w^{n+1} = w^{n}(\left(\Delta x^{n} / \Delta x^{n+1}\right)$ to maintain non-divergence of the flow and hence, avoid shocks. The continuous and gradual adjustment of (1) guarantees no abrupt changes of grid spacing, but rather is gradually nudged towards its value for shallow or deep convection depending on the presence of deep convection. For example, if convection seizes to operate in the SP domain (δ=0), them Δx will slowly return to its value for shallow convection, while in case if a deep cloud development is detected (δ=1), it will be relatively quickly adjusted (over about 6 Δt) to its deep convection value, which means dramatic increase of the domain width to accommodate deep convection.

Preliminary test of the dynamic SP-grid adjustment

The new approach has been tested in the SP-CAM based on CAM v3.5, which co-PI used in his previous research, mostly because of simplicity of implementation and familiarity with the code. The GCM grid was T42 with 30 levels using semi-Lagrangian dynamical core. The SP had 32 grid-columns and Δt=20 s, which correspond to a typical SP-CAM configuration used in the past studies. Each run was 3-year long with prescribed climatological SSTs. The control run (SP) used constant Δx = 4 km and the SPDX run used the dynamically adjusted grid spacing as described above.

Figure 1 shows the global distribution of the annual average Δx. One can see that the new scheme works surprisingly well, that it automatically increases grid spacing

in places of deep convection and decreases it in places where shallow convection predominantly operates. For example, the coarse resolution is predominantly used in well-known regions of the deep convection, such as the ITCZ, while the high-resolution is predominantly used over the regions of subsidence or shallow boundary layer clouds.

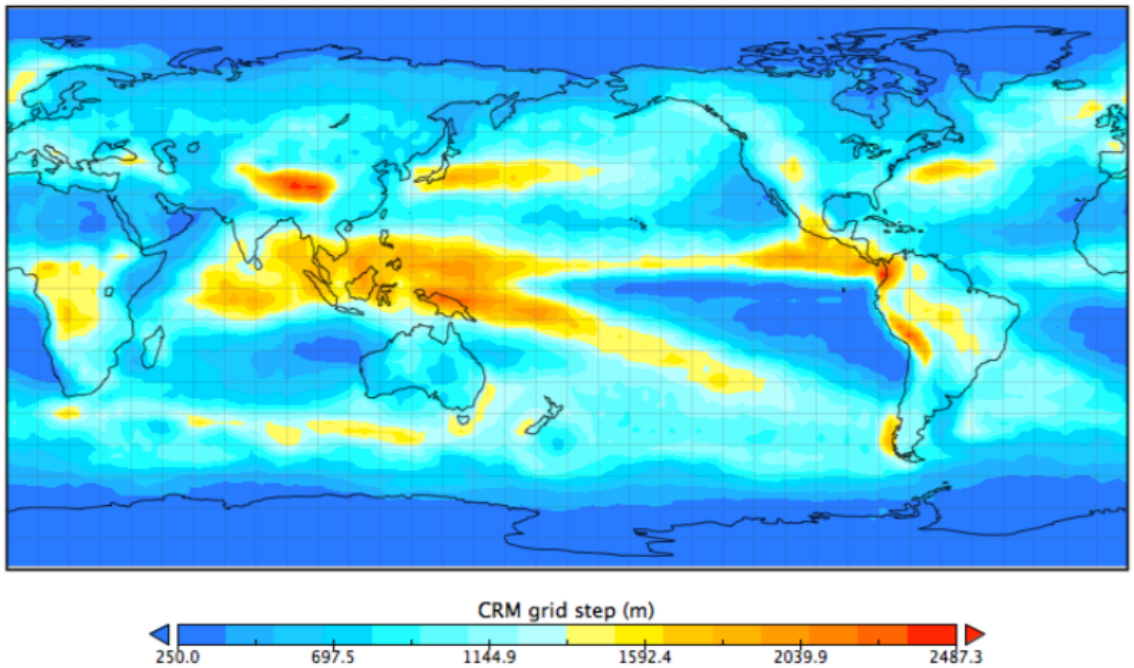

Figure 1 Annual-mean horizontal grid spacing in SPDX run.

Despite apparent technical success of this new technique, the preliminary results indicate that the approach does not necessarily fix the boundary-layer cloud radiative-forcing biases typical for the SP-CAM. While precipitation and precipitable water simulated using the new technique seem to improve (Fig. 2), especially over the intersection of ITCZ and South-Pacific Convergence Zone, the short-wave and long-wave cloud forcing, shown in Fig. 3, have not improved. In fact, the new approach made them even worse than when using the standard SP-CAM. One of the main reasons is probably because the increase of horizontal resolution, unlike common expectations, seems to decrease low-cloud amount. Similar effect has been found in the UP-CAM early simulations with 250-m horizontal grid spacing and 30 vertical levels. One of the remedies is to increase substantially the vertical resolution in the boundary-layer, which can be explored in the future research.

Currently the PI is working on a manuscript describing the new method and which would contain the results of other simulations exploring the role of vertical resolution among others. Overall, the co-PI believes that the new approach has the potential to improve the simulation of clouds and their feedbacks in SP-CAM at substantially lower computational expense than when using the UP-CAM approach.

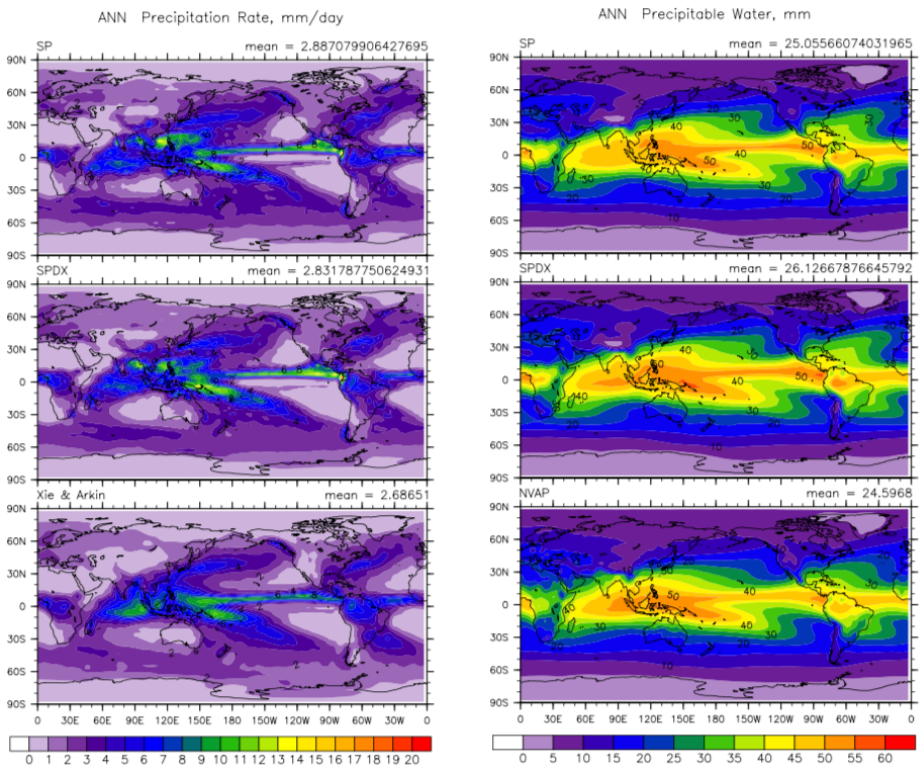

Figure 2 Annual-mean precipitation (left) and precipitable water (right) for SP (top), SPDX (middle) runs and observations (bottom).

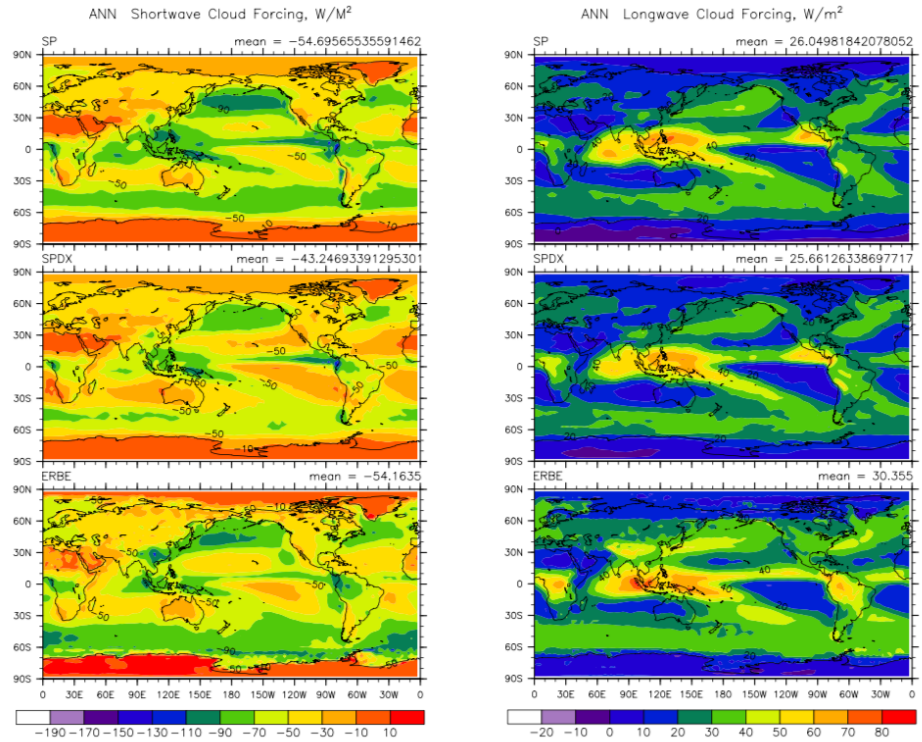

Figure 3 Similar to Fig. 2A, but for shortwave (left) and longwave (right) cloud forcing.

Publications resulted from this project

Parishani, H., M. S. Pritchard, C. S. Bretherton, M. C. Wyant, and M. Khairoutdinov, 2017: Toward low-cloud-permitting cloud superparameterization with explicit boundary layer turbulence, *J. Adv. Model. Earth Syst*, 9, 1542-1571

Parishani, H., Pritchard, M. S.,Bretherton, C. S., Terai, C. R.,Wyant, M. C., Khairoutdinov, M., and Singh, B. (2018). Insensitivity of the cloud response to surface warming under radical changes to boundary layer turbulence and cloud microphysics: Results from the ultraparameterized CAM. , *J. Adv. Model. Earth Syst*, 10, 3139–3158.

Zhou, X. and M.F. Khairoutdinov, 2017: Changes in Temperature and Precipitation Extremes in Superparameterized CAM in Response to Warmer SSTs. *J. Climate*, 30, 9827-9845

Publications in preparation

Khairoutdinov M. F. , C. S. Bretherton, H. Parishani,, and M.S. Pritchard: Super-parameterization with dynamically adjusting horizontal grid spacing to better resolve boundary layer clouds. *In preparation*

Students trained and supported using the funds from this project

Xin Zhou, who graduated with his PhD degree in May 2018.

Wei Zhang, , who graduated with her PhD degree in August 2018.