Expanding the computational frontier of multi-scale atmospheric simulation to advance understanding of low cloud / climate feedbacks

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Abstract

Marine boundary layer clouds are a challenge for climate models. They cover much of the oceans, but they are driven by small-scale turbulent eddies only a few hundred meters across, which in turn respond to the cloud formation. Global climate models have a grid spacing that is far too large to simulate such fluid motions, so they parameterize these cloud formation processes. Different climate modeling groups have designed different parameterizations in which the clouds turn out to be differently sensitive to a warming climate. This drives uncertainties in our best guess at the sensitivity of global warming to greenhouse gas increases.

If these cloud-forming eddies could be directly simulated using the well-known equations of fluid motion, they would no longer need to be parameterized, removing a major source of climate modeling uncertainty. In this project, we overcame software engineering challenges to successfully implemented 'ultraparameterization' (UP), the first global model that does this, and we tested how well it works. We simulated five-year periods with present-day temperatures and with a warmer climate, and we investigated how the UP-simulated clouds responded to climate – the 'cloud feedback' problem. We found little response of clouds at all latitudes to the imposed climate change, which is within the range of predictions of conventional global climate models.

UP is a variation on superparameterization, in which small cloud-resolving models (CRMs) are embedded in each column of the global model. In UP, the CRM grid is fine enough (250 m horizontal × 20 m vertical) to explicitly capture boundary-layer turbulent eddies and associated clouds. Because only one small columnar patch is simulated within each climate model grid cell, this is a million-fold more efficient than simulating the entire globe on this same CRM grid., but achieves much of the same effect for the cloud properties. It doesn't work perfectly. For instance, like conventional climate models, UP simulates too little subtropical stratocumulus cloud, a bias that we are continuing to work to reduce. However, because it directly simulates the turbulent cloud-forming processes, UP is inherently more plausible for simulating how clouds will change in a perturbed climate. In future, we hope to apply UP to another key climate modeling issue: cloud-aerosol interaction and the effect of human-produced aerosols on the climate change we have already experienced and that which is likely to come.

Acknowledgements

At the University of Washington, the funded research was conducted by the PI, supervising research scientist Dr. Peter Blossey and graduate research assistant Pornampai (Ping-Ping) Narenpitak. This project was a collaboration with a UC Irvine group led by Co-PI Dr. Michael Pritchard, Dr. Marat Khairoutdinov of Stony Brook University, and Dr. Balwinder Singh of Pacific Northwest National Laboratory (PNNL), all separately funded by DOE. Dr. Hossein Parishani of UCI played an instrumental role in the core ultraparameterization simulations, and Dr. Pritchard was a very effective and insightful project leader.

Introduction

Our results will be summarized using the abstract of each of the papers supported by this funding (slightly reworded where necessary for clarity) along with a key figure from each paper (with a reworded caption to provide more context). The References provide links to the full papers. The Appendix lists workshop/conference presentations of the funded work whose lead author was from University of Washington. The UC Irvine group also gave several presentations not listed here that included extensive UW contributions.

Paper 1 (Jones et al. 2015): *Mean-state acceleration of cloud-resolving model simulations*

Large eddy simulations and cloud-resolving models (CRMs) are routinely used to simulate boundary layer and deep convective cloud processes, aid in the development of moist physical parameterization for global models, study cloud-climate feedbacks and cloud-aerosol interaction, and as the heart of superparameterized climate models. These models are computationally demanding, placing practical constraints on their use in these applications, especially for long, climate-relevant simulations. In many situations, the horizontal-mean atmospheric structure evolves slowly compared to the turnover time of the most energetic turbulent eddies. We develop a simple scheme to reduce this time scale separation to accelerate the evolution of the mean state. Using this approach, we are able to accelerate the model evolution by a factor of 2–16 or more in idealized stratocumulus, shallow and deep cumulus convection without substantial loss of accuracy in simulating mean cloud statistics and their sensitivity to climate change perturbations. As a culminating test, we apply this technique to accelerate the embedded CRMs in the Superparameterized Community Atmosphere Model by a factor of 2 without any increase in execution time, thereby showing that the method is robust and stable to realistic perturbations across spatial and temporal scales typical in a GCM. Fig. 1 shows that the SPCAM climatology of cloud liquid water path is unaltered by the acceleration, as hoped.

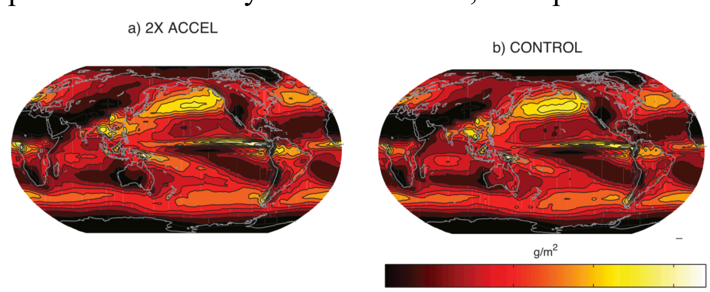

Figure 1: SPCAM annual mean LWP climatology from 4 year simulations using standard 32-column CRMs under (a) 2X accelerated and (b) control configurations (Jones et al. 2015).

Paper 2 (Narenpitak et al. 2017): *Cloud and circulation feedbacks in a near-global aquaplanet cloud-resolving model*

A near-global aquaplanet cloud-resolving model (NGAqua) with fixed meridionally varying sea-surface temperature (SST) is used to investigate cloud feedbacks due to three climate perturbations: a uniform 4 K SST increase, a quadrupled-CO2 concentration, and both combined. NGAqua has a horizontal resolution of 4 km with no cumulus parameterization. Its domain is a zonally periodic 20,480 km-long tropical channel, spanning 46°S–N. It produces plausible mean distributions of clouds, rainfall, and winds. After spin-up, 80 days are analyzed for the control (CTL) and increased-SST (4K) simulations, and 40 days for those with quadrupled CO_2 (4CO2 and 4K+4CO2). As shown in Fig. 2, the Intertropical Convergence Zone width and tropical cloud cover are not strongly affected by SST warming or CO_2 increase, except for the expected upward shift in high clouds with warming, but both perturbations weaken the Hadley circulation. Increased SST induces a statistically significant increase in subtropical low cloud fraction and in-cloud liquid water content but decreases midlatitude cloud, yielding slightly positive domain-mean shortwave cloud feedbacks. CO2 quadrupling causes a slight shallowing and a statistically insignificant reduction of subtropical low cloud fraction. Warming-induced low cloud changes are strongly correlated with changes in estimated inversion strength, which increases modestly in the subtropics but decreases in the midlatitudes. Enhanced clear-sky boundary layer radiative cooling in the warmer climate accompanies the robust subtropical low cloud increase. The probability distribution of column relative humidity across the tropics and subtropics is compared between the control and increased-SST simulations. It shows no evidence of bimodality or increased convective aggregation in a warmer climate.

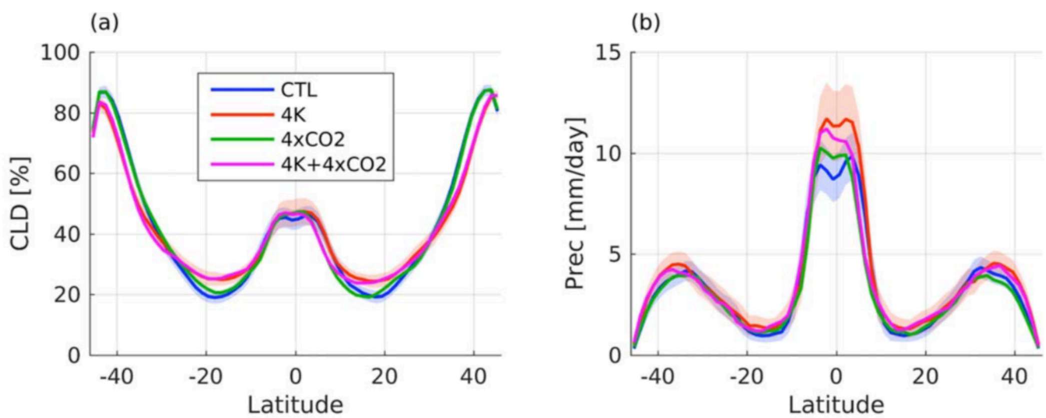

Fig. 2: Zonal-time-mean plots of cloud cover and precipitation for the four 80-day NGAqua simulations. The shaded areas show estimated uncertainty due to natural variability for the CTL and 4K simulations (Narenpitak et al. 2017).

Paper 3 (Parishani et al. 2017): *Towards low cloud-permitting cloud superparameterization*

Systematic biases in the representation of boundary layer (BL) clouds are a leading source of uncertainty in climate projections. A variation on superparameterization (SP) called 'ultraparameterization' (UP) is developed, in which the grid spacing of the cloud-resolving models (CRMs) is fine enough (250 × 20 m) to explicitly capture the BL turbulence, associated clouds, and entrainment in a global climate model capable of multiyear simulations. UP is implemented within the Community Atmosphere Model using 2.8° resolution (~14,000 embedded CRMs) with one-moment microphysics. By using a small domain and mean-state acceleration, UP is computationally feasible today and promising for exascale computers. Short-duration global UP hindcasts are compared with SP and satellite observations of top-of-atmosphere radiation and cloud vertical structure. The most encouraging improvement is a deeper BL and more realistic vertical structure of subtropical stratocumulus (Sc) clouds, due to stronger vertical eddy motions that promote entrainment. Results from 90-day integrations show climatological errors that are competitive with SP (Fig. 3), with a significant improvement in the diurnal cycle of offshore Sc liquid water. Ongoing concerns with the current UP implementation include a dim bias for near-coastal Sc that also occurs less prominently in SP and a bright bias over tropical continental deep convection zones. Nevertheless, UP makes global eddy-permitting simulation a feasible and interesting alternative to conventionally parameterized GCMs or SP-GCMs with turbulence parameterizations for studying BL cloud-climate and cloud-aerosol feedback.

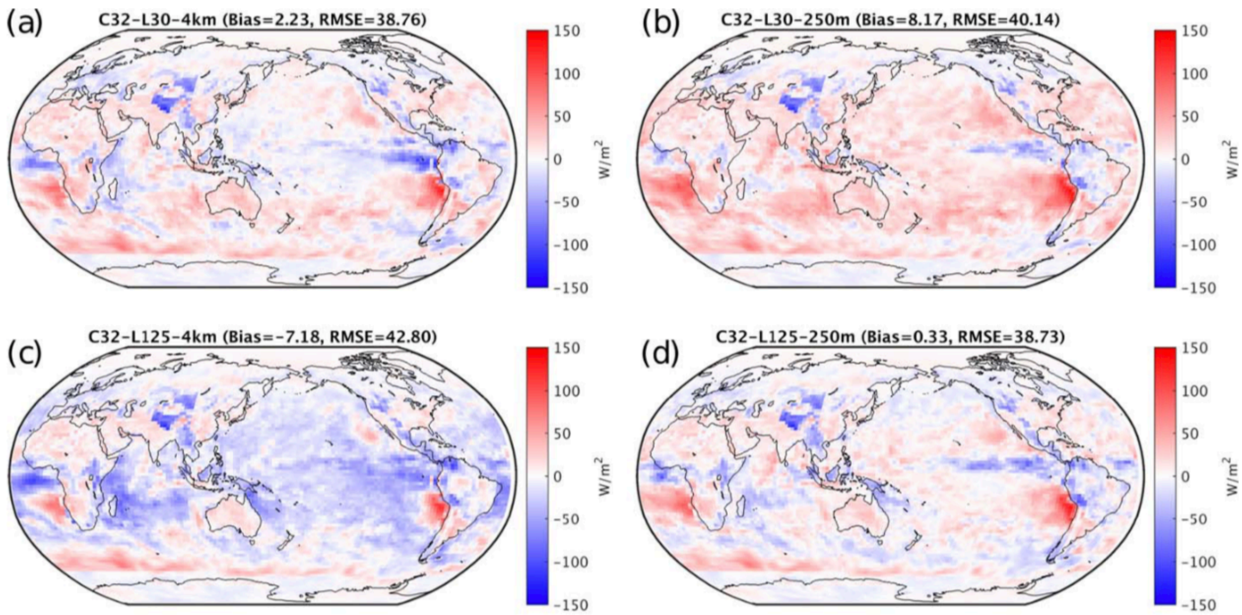

Figure 3. Day 1 ensemble mean absorbed shortwave radiation (ASR) bias of the model: (a) C32-L30–4 km (SP), (b) C32-L30–250 m, (c) C32-L125–4 km, (d) C32-L125–250 m (UP), relative to CERES-SYN estimate of ASR (Parishani et al. 2017).

Paper 4 (Wyant et al. 2018): *The numerical effects of cross-grid flow in simulations of the marine boundary layer.*

In mesoscale and global atmospheric simulations with large horizontal domains, strong horizontal flow across the grid is often unavoidable, but its effects on cloud-topped boundary layers have received comparatively little study. Here the effects of cross-grid flow on large-eddy simulations of stratocumulus and trade-cumulus marine boundary layers are studied across a range of grid resolutions (horizontal × vertical) between 500 m × 20 m and 35 m × 5 m. Three cases are simulated: DYCOMS nocturnal stratocumulus, BOMEX trade cumulus, and a GCSS stratocumulus-to-trade cumulus case. Simulations are performed with a stationary grid (with 4–8 m s^{-1} horizontal winds blowing through the cyclic domain) and a moving grid (equivalent to subtracting off a fixed vertically uniform horizontal wind) approximately matching the mean boundary-layer wind speed. For stratocumulus clouds, cross-grid flow produces two primary effects on stratocumulus clouds: a filtering of fine-scale resolved turbulent eddies, which reduces stratocumulus cloud-top entrainment, and a vertical broadening of the stratocumulus-top inversion which enhances cloud-top entrainment. As shown in Fig. 4, with a coarse (20 m) vertical grid, the former effect dominates and leads to strong increases in cloud cover and LWP, especially as horizontal resolution is coarsened. With a finer (5 m) vertical grid, the latter effect is stronger and leads to small reductions in cloud cover and LWP. For the BOMEX trade cumulus case, cross-grid flow tends to produce fewer and larger clouds with higher LWP, especially for coarser vertical grid spacing. The results presented are robust to choice of scalar advection scheme and Courant number.

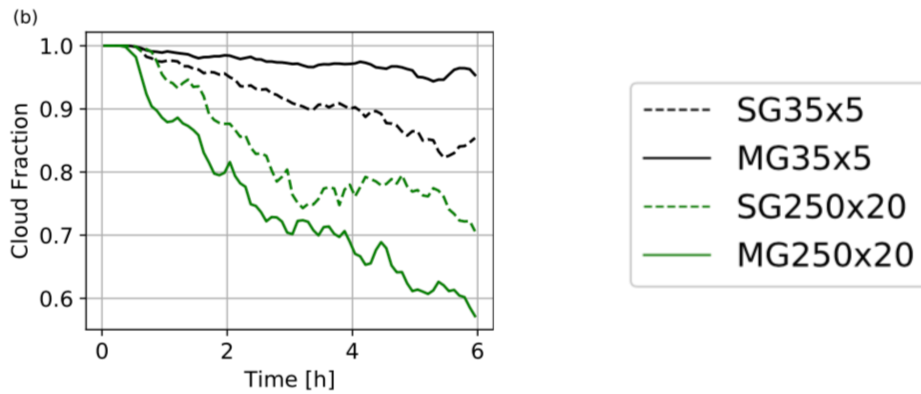

Figure 4: DYCOMS stratocumulus cloud fraction for stationary (SG) and moving-grid (MG) LES with grid spacings of 35m horizontal x 5 m vertical and 250 m horizontal x 20 m vertical (Wyant et al. 2018).

Paper 5 (Parishani et al. 2018): *Insensitivity of the cloud response to surface warming under radical changes to boundary layer turbulence and cloud microphysics: Results from the UltraParameterized CAM*

We study the cloud response to a +4K surface warming in a new multiscale climate model that uses enough interior resolution to begin explicitly resolving boundary layer turbulence (i.e., ultraparameterization or UP). UP's predictions are compared against those from standard superparameterization (SP). The mean cloud radiative effect feedback turns out to be remarkably neutral across all of our simulations, despite some radical changes in both cloud microphysical parameter settings and cloud-resolving model grid resolution (Fig. 5). The overall low cloud response to warming is a positive low cloud feedback over land, a negative feedback (driven by cloud optical depth increase) at high latitudes, and weak feedback over the low-latitude oceans. The most distinct effects of UP result from tuning decisions impacting high-latitude cloud feedback. UP's microphysics is tuned to optimize the model present-day, top-of-atmosphere radiation fluxes against CERES observations, by lowering the cloud ice-liquid phase shift temperature ramp, adjusting the ice/liquid autoconversion rate, and increasing the ice fall speed. This reduces high-latitude low cloud amounts and damps the optical depth feedback at high latitudes, leading to a slightly more positive global cloud feedback compared to SP. A sensitivity test that isolates these microphysical impacts from UP's grid resolution confirms that the microphysical settings are mostly responsible for the differences between SP and UP cloud feedback.

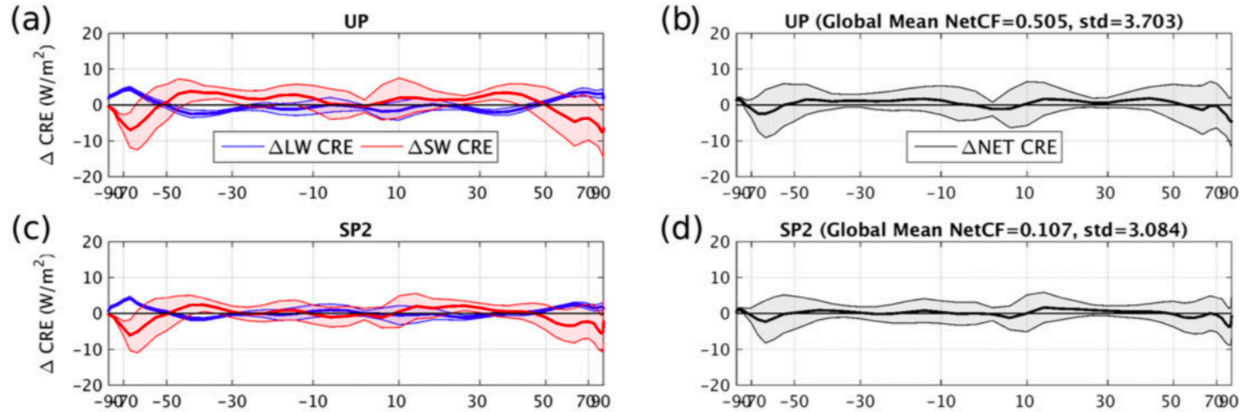

Figure 6. Changes (4 K minus CTRL) in the zonal means of time mean (a, c, and e) shortwave and longwave (red and blue, respectively) and (b, d, and f) net (black) cloud radiative effect for (a, b) UP, (c, d) a version of standard superparameterization, SP2, with the same microphysical parameter settings as in UP. Shading indicates uncertainty ranges due to natural variability (Parishani et al. 2018).

References (publications supported by this grant)

Jones, C., C. S. Bretherton and M. S. Pritchard, 2015. Mean-state acceleration of cloud-resolving model simulations. *J. Adv. Model. Earth Syst.*, 07, doi:10.1002/2015MS000488.

Narenpitak, P., C. S. Bretherton, and M. Khairoutdinov, 2017: Cloud and circulation feedbacks in a near-global aquaplanet cloud-resolving model. *J. Adv. Model. Earth Syst.*, **9**, 1069–1090, doi:10.1002/2016MS000872.

Parishani, H., M. S. Pritchard, C. S. Bretherton, M. C. Wyant, and M. Khairoutdinov, 2017: Towards low cloud-permitting cloud superparameterization. *J. Adv. Model. Earth. Syst.*, **9**, 1542–1571, doi:10.1002/2017MS000968.

Wyant, M. C., C. S. Bretherton, and P. N. Blossey, 2018: The numerical effects of cross-grid flow in simulations of the marine boundary layer. *J. Adv. Model. Earth. Syst.*, **10**, 466-480, doi:10.1002/2017MS001241.

Parishani, H., M. S. Pritchard, C. S. Bretherton, C. R. Terai, M. C. Wyant, M. Khairoutdinov,and B. Singh, 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. https://doi.org/10.1029/2018MS001409.

Summary

Goal: Implement 'ultraparameterization' (UP), a variation on superparameterization in which the grid spacing of the cloud-resolving models (CRMs) is fine to explicitly simulate the turbulence that drives boundary-layer cloudiness in a global climate model capable of multiyear simulations. Test strategies for improving and accelerating UPs computational performance.

Apply UP to predict the response of clouds to a warming climate, a key uncertainty in conventional global climate models.

Main findings:

(1) In this project, we developed a version of UP that can be used for climate-change relevant global simulations of five years or more. Its simulation of global patterns of cloudiness, reflected sunlight, and outgoing longwave radiation are surprisingly similar to normal superparameterization, which uses a much coarser grid. UP simulates too little subtropical stratocumulus cloud, like most conventional global climate models.

(2) By comparing five-year UP simulations with present-day and warm-climate ocean temperatures, we find that a warmer climate has little net change in the radiative effect of the clouds, both globally and in most latitude belts. This is within the range of conventional global climate models.

Questions for further study:

(1) When we started, we thought that a major attraction of UP would be that it should better simulate subtropical stratocumulus clouds, because it has all the modeling ingredients that we believe that should be necessary for that purpose. We spent considerable effort trying to understand why this is not the case, and to our surprise we have been able to show that this bias seems to be driven from the middle of the atmosphere, not the cloud layer. Can we use this finding to help remove the 'dim subtropical stratocumulus' bias?

(2) A motivation for UP was cloud-aerosol interaction, but the software used for this purpose in superparameterized CAM did not parallelize as well as expected so we initially dropped this focus area. However, we think this problem is tractable and worthy of further effort.

Appendix: Presentations supported by this funding and given by UW group members

CMMAP Winter PI Meeting, La Jolla, CA, 1/15
LES acceleration for cloud-resolving and superparameterized simulations

Cloud and Boundary Layer Dynamics Symposium, ETH, Zürich, Switzerland, 6/16
Painting better pictures of climate with a hierarchy of models (invited)

Cloud Feedback Model Intercomparison Project (CFMIP) Workshop, Trieste, Italy, 7/16
Cloud and circulation feedbacks in a near-global aquaplanet CRM

DOE Workshop on Advancing X-cutting Ideas for Computational Climate Science (AXICCS), Rockville, MD, 9/16
Frontiers in simulating multiscale boundary layer cloud organization (invited)

American Geophysical Union Fall Meeting, SF, CA, 12/16 (given by Ping-Ping)

Cloud and Circulation Feedbacks in a Near-Global Aquaplanet Cloud-Resolving Model

CESM Atmospheric Model Working Group meeting, Boulder, CO, 2/17

Ultraparameterization: Global turbulence-resolving simulation for explicit simulation of cloud-topped boundary layers using SPCAM5

AMS Climate Variations Conference, Austin, TX, 1/18

Ultraparameterization: Using large eddy simulation for global simulation of boundary layer clouds and climate