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A Community Atmosphere Model With Superparameterized Clouds

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Simulations by climate models are used to project the climate change expected as atmospheric greenhouse gas concentrations rise. How much will the Earth warm? Will south Asia experience stronger monsoons in the future? Will the American Southwest continue to desiccate? How soon will the Arctic become ice free? How fast and how much will sea level rise? Climate models rely on the idea that sound physical principles can be used to translate basic information, such as emissions of carbon dioxide and aerosols, into changes in the energy balance that influence the formation of clouds, which over time play a key role in shaping future climate response to the emissions.

However, producing virtual clouds from lines of code is not an easy task. Thus, the realism and reliability of climate simulations continues to be limited by the deficiencies of the cloud parameterizations used in global atmospheric models [e.g., *Randall et al.*, 2003].

Although these parameterizations continue to improve, a complementary new approach has recently emerged. This approach involves creating a multiscale atmospheric model in which the physical processes associated with clouds were represented by running a high-resolution model within each grid column of a low-resolution large-scale model. Such enhanced cloud parameterizations explicitly resolve many of the cloud processes that are so difficult to represent in conventional cloud parameterizations.

Developing Models Inside Models

In 1999, National Center for Atmospheric Research (NCAR) scientists Wojciech Grabowski and Piotr Smolarkiewicz created the first multiscale model that in idealized experiments, produced promising simulations of organized tropical convection, which other models had struggled to produce [*Grabowski and Smolarkiewicz,* 1999]. *Grabowski* [2001] subsequently applied the concept to an idealized global simulation and found evidence of large-scale organization of convection.

Inspired by the results of Grabowski and Smolarkiewicz, Colorado State University (CSU) scientists Marat Khairoutdinov and David Randall created a multiscale version of the Community Atmosphere Model (CAM) [*Khairoutdinov and Randall,* 2001]. They removed the cloud parameterizations of CAM and replaced them with a two-dimensional version of Khairoutdinov's cloud-resolving model (CRM). This model used periodic lateral boundary conditions, so that clouds moving out of the CRM domain on one lateral boundary return to the domain on the opposite boundary. They dubbed the embedded CRM a superparameterization and called the global atmospheric model that uses the superparameterization a multiscale modeling framework (MMF). The particular MMF based on their CAM is now called the superparameterized-CAM (SP-CAM).

Over the past several years, scientists from many institutions have explored the ability of SP-CAM to simulate tropical weather systems, the day-night changes of precipitation, the Asian and African monsoons, and other climate phenomena. Cristiana Stan of the Center for Ocean-Land-Atmosphere Studies at George Mason University found that SP-CAM gives improved results when coupled to an ocean model [*Stan et al.*, 2010], and follow-on studies have explored SP-CAM's utility when used as the atmospheric component of the Community Earth System Model (CESM); the coupled model with the atmospheric superparameterization is called SP-CESM. Meanwhile, a second MMF, based on a different global model and a different CRM, has been created by *Tao et al.* [2009].

Much of the research on these multiscale models has been performed under the auspices of the Center for Multiscale Modeling of Atmospheric Processes, a National Science Foundation (NSF) Science and Technology Center for which the lead institution is CSU. Through these modeling efforts, scientists in

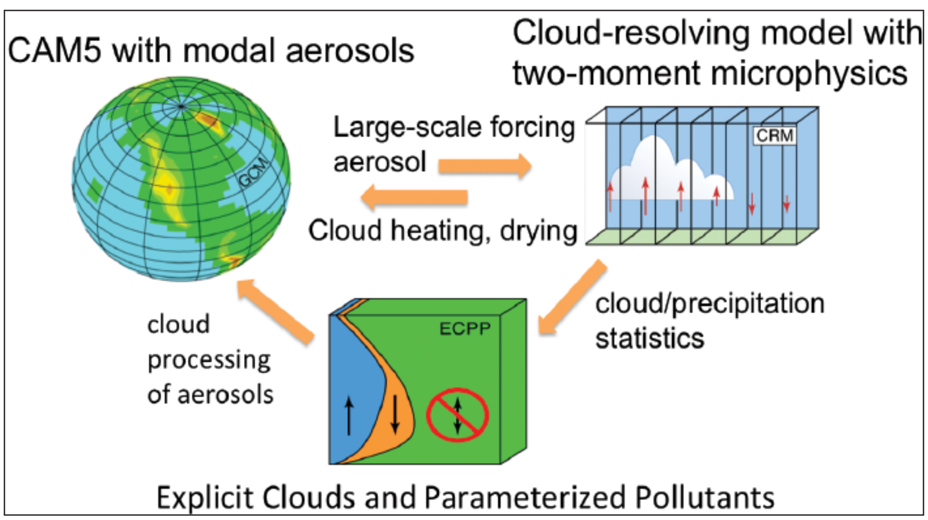

Fig. 1. Configuration of the second generation of the Superparameterized Community Atmosphere Model (SP-CAM). Version 5 of CAM (CAM5, left) simulates the coarse-grid winds and the aerosols used for the radiative heating and two-moment (number and mass) cloud microphysics that drive the cloud-resolving model (CRM). The CRM produces the heating and cloud dynamics that feed back to CAM5 and provides cloud updrafts, cloud liquid water, and precipitation that influence the aerosol through the Explicit Clouds and Parameterized Pollutants (ECPP) module. The ECPP accomplishes this by using cloud information gleaned from the CRM to determine cloud effects on the aerosol. Cloud updrafts are in blue, downdrafts are in orange, and the green area has no vertical motion. Based on Gustafson et al. *[2008, Figure 1].*

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departments across the country are seeking to better understand and quantify the role of clouds in climate change.

Recent SP-CAM Developments

A significantly enhanced version of the SP-CAM has recently been developed at the Pacific Northwest National Laboratory (PNNL), under support from NASA and the U.S. Department of Energy (DOE). As shown in Figure 1, *Wang et al.* [2011a] replaced the very simple representation of cloud droplets and ice crystals of the original SP-CAM with a more general treatment that allows the number of droplets and crystals in clouds to respond more realistically to changes in aerosol particles produced by human activities, and the aerosol particles are now allowed to respond to cloud updrafts, chemical processing in droplets, and removal from the atmosphere by precipitation explicitly simulated by CRM (through a subsidiary model called Explicit Clouds and Parameterized Pollutants (ECPP)). These changes permit estimates of the impact of cloud-aerosol-precipitation interactions on the global energy balance [*Wang et al.,* 2011b] that have been shown to be significantly more realistic than previous estimates [*Wang et al.,* 2012].

SP-CAM in the Community Earth System Model

Over the last 2 years, with support from DOE and from NSF, a team of scientists and software engineers at NCAR, CSU, and PNNL has integrated SP-CAM into the latest version of CESM (version 1.1.1). This version 2 of SP-CAM incorporates enhanced cloud microphysics and the coupling to the aerosol model developed at PNNL as well as some additional options. Version 2 is stable, is compatible with CESM version 1.1.1, and is now available to researchers to use as part of an Earth system model at https://svn-ccsm-release.cgd.ucar.edu/model_development_releases/spcam2_0-cesm1_1_1.

Plans for the Future

SP-CAM continues to evolve at a rapid pace. It relies on parameterizations of turbulence and small clouds, which cannot be resolved even on CRM's relatively fine grid. Several improved parameterizations of turbulence and shallow convection are being tested. In addition, SP-CESM is being refined so that the coupling of the atmosphere and the land surface occurs on the CRM's grid. This will allow simulation of small-scale atmosphere–land surface interactions, associated with heterogeneous vegetation, wet spots on the ground, cloud shadows, and gust fronts. In addition, *Jung and Arakawa* [2010] have developed and tested a radically redesigned MMF that eliminates the two-dimensionality and periodic boundary conditions of CRM.

Ultimately, the goal is to explicitly resolve clouds with a global cloud-resolving model (GCRM). As the outer grid size of *Jung and Arakawa*'s [2010] MMF is refined to that of CRM, their MMF naturally converges to a GCRM.

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