# BREAKING THE CLOUD PARAMETERIZATION DEADLOCK

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Progress on the cloud parameterization problem has been too slow. The authors advocate a new approach that is very promising but also very expensive computationally.

**CLOUDS AND CLIMATE: A PROBLEM THAT REFUSES TO DIE.** Clouds of many varieties fill the global atmosphere (Fig. 1). They are composed of drops and crystals with scales on the order of microns to millimeters. They are associated with convection and turbulence on scales of meters to kilometers. They are organized within mesoscale and synoptic-scale dynamical systems that interact with the global circulation of the atmosphere.

The representation of cloud processes in global atmospheric models has been recognized for decades

**FIG. 1. A full-disk visible image showing many cloud systems, including the intertropical convergence zone of the tropical eastern Pacific Ocean, marine stratocumulus clouds west of both South America and North America, and frontal clouds in the midlatitudes of both hemispheres.**

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(e.g., Arakawa 1975; Charney 1979; Houghton et al. 2001) as the source of much of the uncertainty surrounding predictions of climate variability. Despite the best efforts of our community, and notwithstanding the achievement of significant advances, summarized below, the problem remains largely unsolved. At the current rate of progress, cloud parameterization deficiencies will continue to plague us for many more decades into the future. The cloud parameterization problem is "deadlocked," in the sense that our rate of progress is unacceptably slow. A new and different strategy is needed; we offer such a strategy in this paper.

Let us first step back and ask: What is parameterization and why is it necessary? The basic physical equations describe the behavior of the atmosphere on small scales. From these we derive equations that describe the behavior of the system on larger scales. The large-scale equations contain terms that represent the effects of smaller-scale processes. A "parameterization" is designed to represent the effects of the smaller-scale processes in terms of the large-scale state. Parameterizations are much more than curve fits. They are statistical theories that describe the interactions of small scales with larger scales. Parameterizations typically involve idealizations as well as "closure assumptions" that are, at best, only approximately valid.

Note the irony here: Even though the basic physical equations in which we have the most confidence describe small-scale processes, in practice it is the effects of those small-scale processes that are incorporated into our models through the use of uncertain closure assumptions. It is ironic that we cannot represent the effects of the small-scale processes by making direct use of the well-known equations that govern them.

Or can we?

**CLOUDS ARE COMPLICATED.** To set the stage for the later discussion, it is useful to begin by reviewing the appalling complexity of the cloud parameterization problem, and the weapons that have been brought to bear on it up to this point.

*Hot towers and their environment.* Bjerknes (1938) taught us that for dynamical reasons cumulus convection prefers to organize itself in the form of narrow, intense updrafts embedded in a broad, slowly subsiding environment (Fig. 2). His conclusion implies that the thermodynamic properties of the slowly subsiding environment are very nearly the same as those of the large-scale mean. This idea has been extensively used in cumulus parameterizations based on the mass-flux concept (e.g., Arakawa 1969; Arakawa and Schubert 1974), which have now been almost universally adopted in large-scale models.

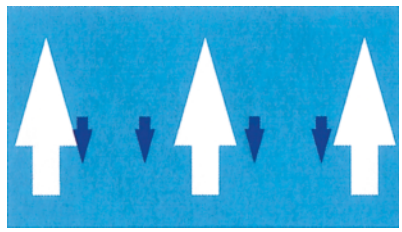

**FIG. 2. Cumulus circulations organize themselves into narrow, intense saturated updrafts with broad, slowly subsiding unsaturated air in between.**

Riehl and Malkus (1958) deduced from observations that the penetrative convective updrafts analyzed by Bjerknes (1938), which they dubbed "hot towers," play an essential role in the vertical transport of energy, especially in the Tropics. More than 40 years later, our understanding of the interactions of these hot towers with the global circulation is still in a fairly primitive state. For example, we do not adequately understand what determines the rate of entrainment of "environmental" air into the updrafts, or how entrainment affects the evolution of a convective cloud system. Cumulus entrainment entails the dilution of the convective updraft by dry, cool environmental air. Current parameterizations incorporate the effects of entrainment through simple assumptions that are difficult to test against observations or even against high-resolution model results (e.g., Lin and Arakawa 1997a,b). The environment of the hot towers is typically assumed to be uniform, but in reality its properties vary on unresolved scales, due in part to the accumulated humid corpses of deceased cumuli. The properties of the entrained air must, therefore, depend on which part of the variable environment in which an updraft happens to find itself. In addition, the representation of microphysical processes in hot towers is extremely crude, and this weakness is difficult to address, given the highly simplified representations of cloud dynamics typically used in parameterizations for large-scale models.

*Cold showers.* Some of the precipitation formed in convective towers falls through the unsaturated air adjacent to the towers. As it evaporates, it cools and moistens the environment. This drives convective-scale downdrafts, which lead to further cooling and moistening. Parameterizations of these effects have been proposed by Johnson (1976), Cheng and Arakawa (1997), and others. Nevertheless, it is fair to say that at the present time downdrafts are either not parameterized or crudely parameterized in large-scale models. Among the effects that are missing but important is the injection of downdraft air into the planetary boundary layer (PBL), which cools and dries the PBL and simultaneously enhances the PBL turbulence and the surface fluxes.

*Stratiform clouds.* Most of the radiatively important cloudiness is stratiform in nature (Fig. 3). We define stratiform clouds as those that are neutrally buoyant in an area-averaged sense (Randall and Fowler 1999). Smagorinsky (1960) proposed a parameterization of stratiform cloudiness based on relative humidity, without addressing the mechanics of cloud formation and dissipation. Following Smagorinsky, early general circulation models (GCMs) parameterized stratiform clouds in terms of the large-scale relative humidity. Sundqvist (1978) advocated the explicit prediction of condensed water mixing ratios in large-scale models, by means of simple microphysical parameterizations. Following his lead, many large-scale modelers began, during the 1980s and 1990s, to predict the spatial distribution of condensed water.

**Fig. 3. Stratiform clouds cover large areas and so are radiatively important. They also produce large amounts of precipitation, even in convectively active regions.**

**Fig. 4. Cumulus convection generates stratiform cloudiness through detrainment of ice and liquid. A major portion of all stratiform cloudiness is produced through such detrainment.**

Nevertheless, today's stratiform cloud parameterizations are very rough caricatures of reality. For example, until recently it has been assumed that the temperature of a stratiform cloud is the same as the temperature of its clear environment at the same level. As mentioned above, this assumption is consistent with the very definition of stratiform cloudiness, but we must ask how it is possible for the in-cloud and environmental temperatures to remain close despite the fact that the cloudy air experiences phase changes, radiative heating, and turbulent fluxes that could easily drive its temperature away from that of the environment. For a discussion of this issue, see Randall and Fowler (1999).

*Interactions between convective and stratiform clouds.* Many stratiform clouds are produced by the detrainment of condensed water from cumulus updrafts (Fig. 4). Arakawa and Schubert (1974) explicitly recognized detrainment of condensed water as a source of stratiform clouds. This stratiform cloud formation "hook" in the Arakawa–Schubert cumulus parameterization went unused for more than a decade, because stratiform clouds were neglected by the research community, which instead focused its attention on the more dramatic and dynamically active cumulus clouds. In fact, during the 1970s and 1980s, cumulus parameterizations were extensively tested against observations without even accounting for the effects of the attendant stratiform clouds.

Tiedtke (1993) took another important step forward, developing a comprehensive parameterization in which cumulus detrainment acts as a source of condensed water and cloud area, both of which are predicted in his model. An extension of Tiedtke's approach has been developed by Randall and Fowler (1999).

Prognostic parameterizations of stratiform cloudiness and its production by convective detrainment have led to major improvements in both NWP scores and climate simulations. Again, this is progress. Nevertheless, there are many remaining difficulties. Model results are sensitive to the microphysical properties of the detrained air (e.g., Fowler and Randall 2002). The very concept of detrainment is somewhat murky, and the conditions that trigger detrainment are imperfectly understood. It appears likely that future cloud parameterizations will represent stratiform and convective clouds in a unified framework (Arakawa 2000).

*Mesoscale organization.* Meanwhile, all atmospheric scientists know that clouds are often highly organized on the "mesoscale" (Fig. 5), which can be loosely defined as the range of scales between 10 and 100 km. Houze (1989) and colleagues have emphasized the importance of the mesoscale anvil cloud precipitation and the mesoscale vertical motions associated with anvil clouds. They view a mesoscale system as a thermodynamically active extension of the cumulus system. As mentioned earlier, the mesoscale environment can be significantly more moist, and, therefore, more nurturing to growing cumulus clouds, than the large-scale mean. Stratiform cloud processes are often organized on the mesoscale.

In addition, there are of course important dynamical processes in mesoscale convective systems. These are emphasized by Moncrieff and colleagues (e.g., Moncrieff 1992), who also focus on convective and mesoscale momentum fluxes and the geometrical structures of mesoscale convective systems.

GCMs are just beginning to include simple representations of these important mesoscale processes (Donner 1993; Randall and Fowler 1999; Donner et al. 2001). It is fair to say that at this time no existing GCM includes a satisfactory parameterization of the effects of mesoscale cloud circulations.

*Turbulence.* Virtually all clouds are turbulent. The reason is that in-cloud turbulence is driven by cloud-top radiative cooling and cloud-base radiative warming, helped along by phase changes within the convective turbulence.

The rate of entrainment into cumuli is partly determined by turbulent processes (Fig. 6). Turbulence in stratiform clouds leads to the entrainment of the warm, dry air that often lies immediately above the top of a stratiform cloud layer. Such entrainment can easily produce holes in the cloud layer, and so the rate of entrainment affects the fractional cloudiness.

Shallow cumuli are essentially the saturated rising branches of convective turbulence in the PBL. In this limit, the parameterization of turbulence and the parameterization of convection overlap. Future parameterizations should represent PBL processes and moist convective processes in a unified framework (e.g., Lappen and Randall 2001).

In his classic study of boundary layer stratocumulus clouds, Lilly (1968) pointed out that there are very strong and "fast" interactions among cloudiness, turbulence, and radiation. The most immediate effect of cloud-induced radiative heating or cooling is to alter the turbulent and cloud-scale circulations, which can respond very quickly to such forcing. The large-scale circulation also feels these radiative effects, but it responds more slowly, so that in the end it is the combined effects of microphysics, turbulence, and radiation that influence the large scale. From this point of view, the large-scale effects of microphysics, turbulence, and radiation should be parameterized as closely coupled processes acting in concert, rather than as "separate" processes. A few GCMs have begun incorporating Lilly's ideas, for boundary layer clouds only (e.g., Randall et al. 1985). Turbulence–radiation interactions are also at work in most other types of stratiform clouds; for example, cirrus, and in fact the most recent version of the University of Cali-

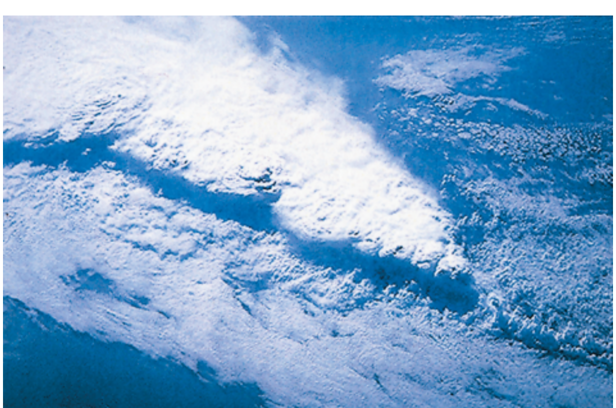

**FIG. 5. An example of a mesoscale convective system over FL, as seen from the space shuttle.**

**FIG. 6. The turbulent edge of a cumulus cloud, where lateral entrainment is occurring.**

fornia, Los Angeles (UCLA) GCM includes Köhler's (1999) parameterization of the effects of radiative destabilization on the decay time scale of cirrus ice water content. Further discussion will be given by W. Grabowski (2003, personal communication) in a forthcoming paper.

*Radiation.* According to some radiative transfer specialists [e.g., Global Energy and Water Cycle Experiment (GEWEX) Radiation Panel meeting, October 2001], a key factor limiting the accuracy of radiative fluxes and heating/cooling rates is the inadequacy of the simulated atmospheric state provided as input to the radiation parameterization. This input includes information about the nature of the cloud particles (phase, shape, size, etc.) as well as the geometry of the cloud field (e.g., "radiative overlap"). Attempts to account for radiative overlap can add significantly to the computational cost of a model, despite the fact that they are based on simple assumptions without the benefit of real information about the geometry of the simulated cloud field.

*Microphysics.* Microphysical processes are of course implied in the mere use of the word "cloud." They include cloud formation and evaporation/sublimation, precipitation formation via collisions and coalescence, the collection of cloud particles by falling precipitation, and complicated precipitation-induced interactions among multiple cloud layers ("microphysical overlap," see Fig. 7; Jakob and Klein 2000). Some current GCMs still do not include microphysics parameterizations at all. Others contain relatively crude "bulk" microphysics parameterizations similar to those used in many mesoscale models. Much more detailed microphysics parameterizations exist, for example, some that keep track of many particle size "categories," but these have never been used in GCMs. A strong disincentive to using such detailed schemes in GCMs is that the results obtained would depend critically on cloud-scale dynamical processes, which are at best only crudely parameterized in all existing GCMs. In other words, the required input is not available.

The properties of cloud particles are strongly influenced by the ambient aerosols, which in turn depend on chemical processes in the atmosphere. Existing GCMs represent the effects of aerosols on microphysics very crudely or (in most cases) not at all. Again, the required input is not available, at least not in robust form.

*Overwhelming complexity.* The preceding discussion is intended to drive home the simple but important point that the cloud parameterization problem is overwhelmingly complicated. Cloud parameterization developers (a small group, even worldwide) are struggling to identify the most important processes on the basis of woefully incomplete observations. At the same time, they are trying to compute the statistics of these processes that matter for the large-scale circulation and climate, without directly representing the cloud processes at their "native" space and time scales. There is little question why the cloud parameterization problem is taking a long time to solve: It is very, very hard.

We should be asking ourselves: *Is it really possible to parameterize all of this complexity with quantitative accuracy?* Work on cloud parameterizations for large-scale models began about 40 years ago (Fig. 8). Collectively, we, the authors of this paper, have been working on the problem for almost a century. Are we having fun yet? Definitely yes. Cloud parameterization is a beautiful, important, infinitely challenging problem, and we continue to be fascinated and excited by it. We and the other members of our research community have made important progress, of which we should be proud, and we have no doubt that progress will continue. Nevertheless, a sober assessment suggests that with current approaches the cloud parameterization problem will not be "solved" in any of our lifetimes.

To give an indication of what the current approaches are, we briefly sketch a work in progress

**Fig. 7. Precipitation falling from elevated cumuli. When there are multiple cloud layers, such precipitation can fall through either clear or cloudy air. Such microphysical overlap influences the precipitation rate and other processes.**


**Fig. 8. Cloud parameterization research (blue line) began about 40 yr ago.**

(Randall and Fowler 1999), which is essentially an extension of Tiedtke's (1993) parameterization. In this approach, convective updrafts and downdrafts coexist with a partly cloudy environment (Fig. 9). The clear and cloudy regions have different thermodynamic properties and different vertical velocities. The cloudy region is turbulent, while the clear region is not. To represent the cloud processes at work, we use the following prognostic variables that represent variability on multiple subgrid scales:

- water vapor and temperature in clear and cloudy regions,
- the mixing ratios of cloud water and cloud ice in the cloudy air,
- the fractional area covered by stratiform clouds,
- the mixing ratios of rain and snow,
- the cumulus mass flux, and
- the mesoscale mass flux.

This approach has been implemented in the Colorado State University GCM. It is pretty complicated. With additional refinements, including a planned parameterization of turbulence (following Lappen and Randall 2001), conventional approaches of this type can easily become almost as complicated as a high-

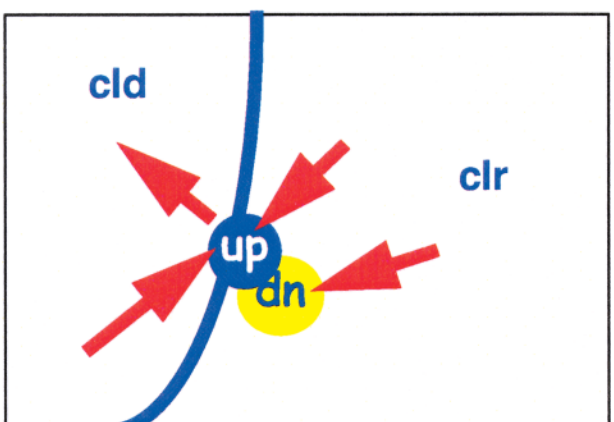


**FIG. 9. Sketch illustrating a cloud parameterization currently being tested in a general circulation model (Randall and Fowler 1999). A stratiform cloudy region (cld) and a clear region (clr) coexist within a GCM grid box (black rectangle). The blue curve separates the two regions. The blue dot labeled up represents the ensemble of convective updrafts. The updrafts detrain cloudy air, which joins the stratiform cloud. Convective downdrafts occur in the precipitation shafts that fall from the convective updrafts. The updrafts entrain air from both the cloudy and clear regions. In this sketch, the downdraft (labeled dn) is shown as entraining only from the clear region. The cloudy region is turbulent, but the clear region is nonturbulent.**

resolution model, and yet, at least for the foreseeable future, they will not provide physically based representations of cloud overlap in the radiative and microphysical senses, a realistic representation of aerosol effects, etc.

There are at least two different senses in which conventional cloud parameterizations are becoming more complicated. The number of prognostic variables associated with a parameterization is one measure of its complexity, and this number is indeed rapidly increasing. In addition to this *numerical complexity,* however, we must also confront *conceptual complexity,* which is also rapidly increasing, largely because, as discussed earlier, our parameterizations are purely statistical theories.

We can hope that by further pursuing the conventional approaches to cloud parameterization we will learn, eventually, how to make a parameterization that is much more realistic than what we have today, but not much more complicated. That would be nice, but *there is no guarantee that it is possible.* We suspect that the more realistic parameterizations of the future will be dramatically more complicated, in both the numerical and conceptual senses, than the less realistic ones we have now.

The need for more realistic simulations of the role of clouds in climate is so urgent, so critical, that we must pursue all available routes to progress. One promising and relatively new option is to use high-resolution models as tools to accelerate and otherwise optimize the process of cloud parameterization development.

## CLOUD SYSTEM–RESOLVING MODELS.

Since the mid-1980s, "cloud system–resolving models" (CSRMs) have been used as tools for the evaluation of cloud parameterizations (e.g., Krueger 1988; Xu and Krueger 1991). By definition, CSRMs have resolutions fine enough to represent individual cloud elements, and space–time domains large enough to encompass many clouds over many cloud lifetimes. CSRMs can be compared with "single-column models" (SCMs), which are the column-physics components of GCMs, surgically extracted from their host GCMs. Both CSRMs and SCMs can be driven by observations of large-scale weather systems (e.g., Randall and Cripe 1999). The logical relationships among CSRMs, SCMs, and GCMs are shown in Fig. 10.

The earliest CSRM was developed by Yamasaki (1975), Krueger (1988), Arakawa and Xu began applying CSRMs to the parameterization problem in the mid-1980s. Today there are dozens of CSRMs, at various centers around the world. Until recently CSRMs were limited to two dimensions (2D) in order to limit the computational expense, but with today's computer's 3D CSRMs are quite practical for many applications.

CSRMs give better results than SCMs, at least for deep convective clouds and the stratiform clouds associated with them. One would certainly hope so, considering that the computational cost of running a CSRM is hundreds or thousands of times greater than that of running an SCM. The GEWEX Cloud Systems Study (GCSS) and Atmospheric Radiation Measurement (ARM) have actually *demonstrated* that CSRMs give better results than SCMs, through a number of case studies, as discussed by Randall et al. (2003).

How can we use CSRMs in cloud parameterization research? CSRMs can also be used to confront models with data, in order to answer questions about parameterizations, for example, to test whether ideas for parameterizations have merit. As discussed by Randall et al. (2003), this is a key facet of the research strategy adopted by GCSS.

It is often said that CSRMs can be used to *develop* improved parameterizations, but this is not at all straightforward. The key ingredients of better parameterizations are better ideas. Constructing and running a CSRM does not, in itself, generate better ideas. It is true that insightful analysis of CSRM results can sometimes suggest an idea via the "Aha!" mechanism. This is particularly true in the case of idealized simulations, in which the interactions of physical processes are easier to discern than in the real atmosphere. For example, Xu et al. (1992) used idealized simulations with a CSRM to identify and quantify the deterministic and nondeterministic components of the response of the cloud system to prescribed periodic large-scale forcing. Köhler (1999) used results from idealized simulations with a CSRM to parameterize the decay time scale of cirrus clouds in terms of the radiative destabilization of the cloud layer. Zulauf and Krueger (2002) found in idealized simulations with a CSRM that anvils produced by convective detrainment spread horizontally due to previously undocumented interactions among radiative warming, lateral turbulent entrainment, and mesoscale circulations. A CSRM is an ideal tool—in some cases perhaps the only possible tool—for such studies.

Can we use CSRMs for anything else? Read on.

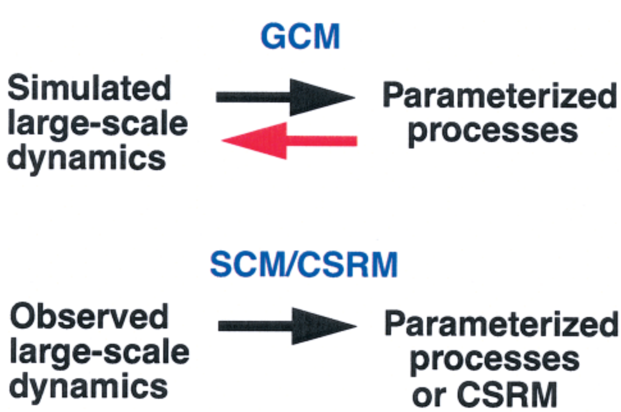


**FIG. 10. In a GCM, the simulated large-scale dynamics and the parameterized processes interact in both directions. SCMs and CSRMs can be driven with observations (or with GCM output), but in this case the interaction is in one direction only.**

**SUPERPARAMETERIZATIONS.** Given the cloud-simulating prowess of CSRMs, we inevitably find ourselves daydreaming about using a global CSRM to perform climate simulations. Here it is useful to work through some rough numbers. Existing GCMs used for climate simulation typically have on the order of $10^4$ grid columns. The average grid cell of such a model is about 200 km across. In contrast, a hypothetical global model with grid cells 2 km wide, that is, a global CSRM, would have about $10^8$ grid columns, that is, about $10^4$ times as many as current climate models. To maintain computational stability (and accuracy), a global model with cells 2 km across would have to use time steps about 100 times shorter than the time steps of current climate models. The total increase in computation, relative to current climate models, would, thus, be on the order of $10^6$. In a few more decades it will become possible to use such global CSRMs to perform century-scale climate simulations, relevant to such problems as anthropogenic climate change. Today's graduate students may be lucky enough to work with such models, later in their careers.

There is another approach, however, which can be used now. As first suggested by W. Grabowski (Grabowski and Smolarkiewicz 1999; Graborwski 2001), we can run a CSRM as a "superparameterization" inside a GCM.[1] A GCM that uses a superparameterization can be called a "super-GCM."

Grabowski implemented a 2D CSRM inside a drastically simplified global model with globally uniform SSTs, no mountains, etc. Figure 11 illustrates the idea. The CSRM does not fill the large-scale model's grid box.

[1] A similar suggestion was made by R. Laprise and P. Bechtold in an unpublished manuscript (1999 and 2000), entitled "On the use of a semi cloud-resolving model (SCRM) for representing moist convection in large-scale models."

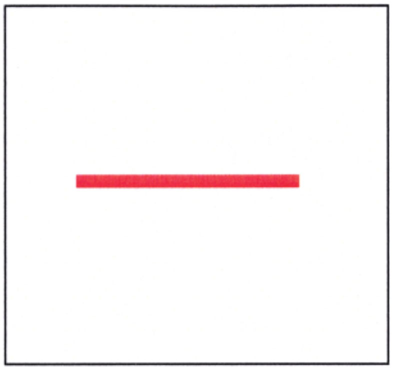

**FIG. 11. Grabowski embedded a 2D CSRM inside each grid cell of a global model. Here the black box represents a GCM grid cell. The red bar represents the 2D CSRM. In this example, the CSRM is oriented east–west (i.e., left–right in the sketch). Grabowski and Smolarkiewicz (1999) and Grabowski (2001) experimented with a north–south orientation as well. As would be expected, the results obtained depend to some extent on the orientation chosen. See Grabowski's papers for further discussion.**

Instead, it represents a "sample" of the box, analogous to a population sample used in an opinion poll. The CSRM computes statistics (e.g., the precipitation rate and fractional cloudiness) for the sampled portion of a large-scale model's grid column, and these are applied to the entire grid column, much as an opinion pollster computes statistics from a sample of a population and applies them to the whole population.

Because Grabowski's CSRM was two-dimensional, he had to specify its orientation. In Fig. 11 the orientation is arbitrarily taken to be "east–west." Grabowski performed experiments with alternative choices for the orientation, and found that the results obtained varied to some extent, as would be expected.

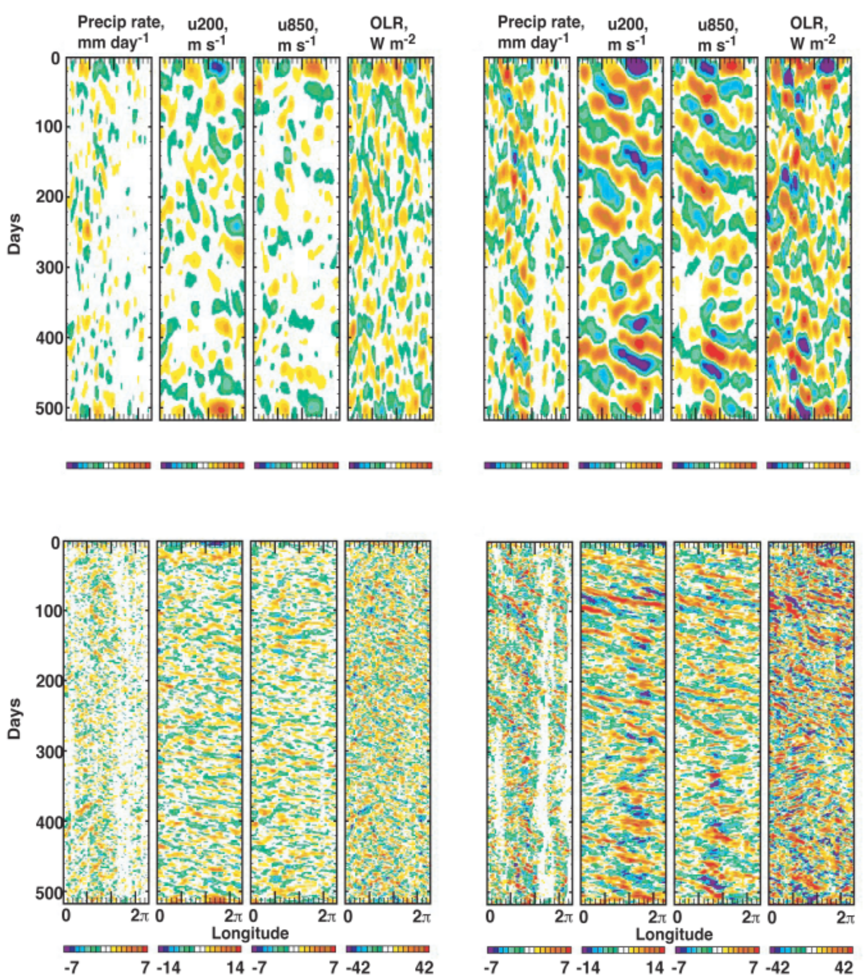


**FIG. 12. Hövmöller diagrams for the precipitation rate, 200-mb zonal wind, 850-mb zonal wind, and OLR in a control run with the T21 CAM, and in an experiment with the same model modified to use the superparameterization. In the top two panels, the results are filtered to show variability with periods in the range 20–100 days. The bottom two panels show variability in the 2–20-days range.**

Grabowski used periodic boundary conditions, so that a simulated cloud system that moved out of one side of the CSRM domain moved back in on the opposite side. This made it impossible for cloud systems to directly propagate from the CSRM in one GCM grid column to the CSRM in a neighboring column, although of course the propagation of a large-scale weather system, as represented by the large-scale model, could cause the CSRMs in neighboring large-scale grid columns to develop cloud systems that "appear" to propagate between neighboring grid columns.

Grabowski obtained results that look physically realistic, for example, a tropical disturbance similar to the observed Madden–Julian oscillation (MJO; Madden and Julian 1994; Slingo et al. 1996). Because the global model used was so highly idealized, caution is needed in interpreting Grabowski's results as a true MJO simulation, but without question his results are very provocative and interesting.

Inspired by Grabowski's idea, Khairoutdinov and Randall (2001; hereafter KR) embedded the 2D CSRM developed by Khairoutdinov as a superparameterization in the Community Atmosphere Model (CAM), which is the atmosphere submodel of the Community Climate System Model (CCSM; Blackmon et al. 2001). The CAM is a true GCM; it has realistic topography, sea surface temperatures, a full suite of physical parameterizations, etc. In the study of KR, the CSRM takes the place of the CAM's stratiform and convective cloud parameterizations. Because of the large computing requirements (discussed below), KR performed only a 2-month simulation, using T42 resolution, and analyzed results from the second month, which was a January. Without any tuning of the model, they were able to obtain simulations of precipitation, the earth's radiation budget, and precipitable water, which are at least comparable in quality to those of a control run that uses conventional parameterizations.

More recently, KR have extended this work by performing an annual cycle simulation with a low-resolution (T21) version of the super-CAM. As shown in the top portion of Fig. 12, the model produces a vigorous MJO, in contrast to the "control" run, in which the MJO is virtually nonexistent. The simulated MJO obtained with the superparameterization has several realistic features. For example, the disturbances propagate slowly over the warm water of the Indian Ocean and the western Pacific warm pool, and more rapidly east of the date line. The simulated seasonal change of the MJO is also consistent with observations. The composite structure of the simulated MJO is quite realistic (Fig. 13). As seen in Fig. 14, the simulated outgoing longwave radiation (OLR) anomalies are, if anything, somewhat stronger than observed, suggesting that the simulated cloud-top heights are exaggerated.

The lower portion of Fig. 12 shows higher-frequency variability as simulated by the conventional GCM and the super-GCM. The super-CAM produces highly organized and convectively coupled tropical waves, including realistic-looking Kelvin modes. In the control run the Tropics are unrealistically quiet. Additional discussion will be presented elsewhere; extensive further tests of the super-CAM are being carried out as this paper is being written.

To summarize the preceding discussion, we have demonstrated, by example, that superparameterizations can be incorporated into GCMs without much difficulty, and with good results, including a robust simulation of the MJO. This is a fairly modest claim.

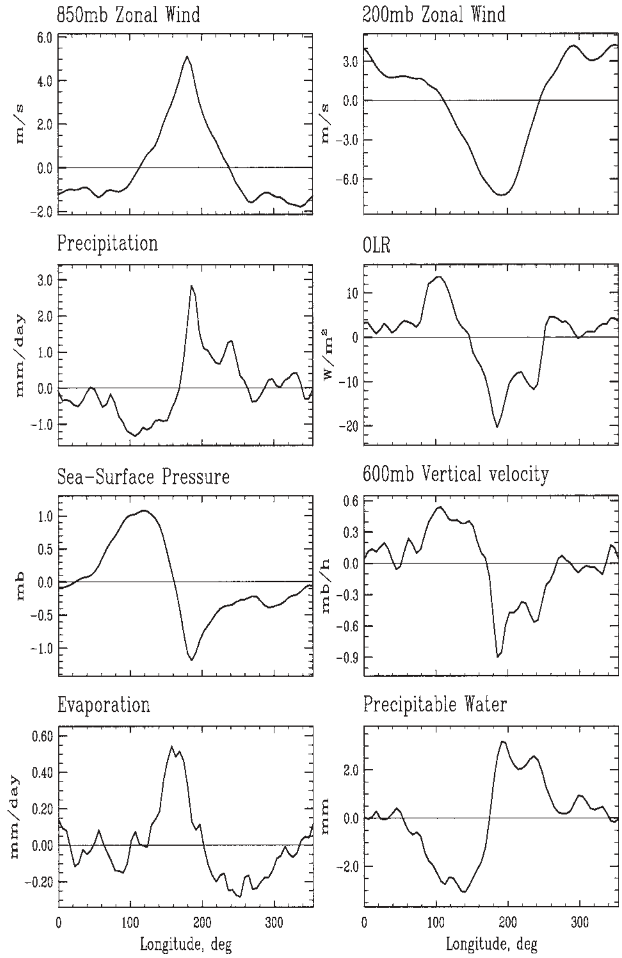


**FIG. 13. Composite structure of the simulated MJO shown in Fig. 12. The 850- and 200-mb zonal wind anomalies are out of phase, as expected. The precipitation peaks slightly to the east of the maximum 850-mb zonal wind. The OLR is a mirror image of the precipitation rate. The midtroposphere vertical velocity is upward in the precipitation maximum, and downward to the west of the precipitation maximum. The surface evaporation rate peaks to the west of the precipitation maximum, as observed. The precipitable water peaks to the east of the precipitation maximum.**

In addition, however, we emphasize there are many a priori reasons to believe that superparameterizations can provide more realistic, more reliable, and generally more useful simulations of weather and climate; they are as follows:

- Super-GCMs explicitly simulate deep convection, including mesoscale organization (e.g., squall lines), downdrafts, anvils, etc.
- Super-GCMs explicitly simulate fractional cloudiness, down to a scale of a few kilometers.
- Super-GCMs explicitly simulate cloud overlap in the radiative sense.

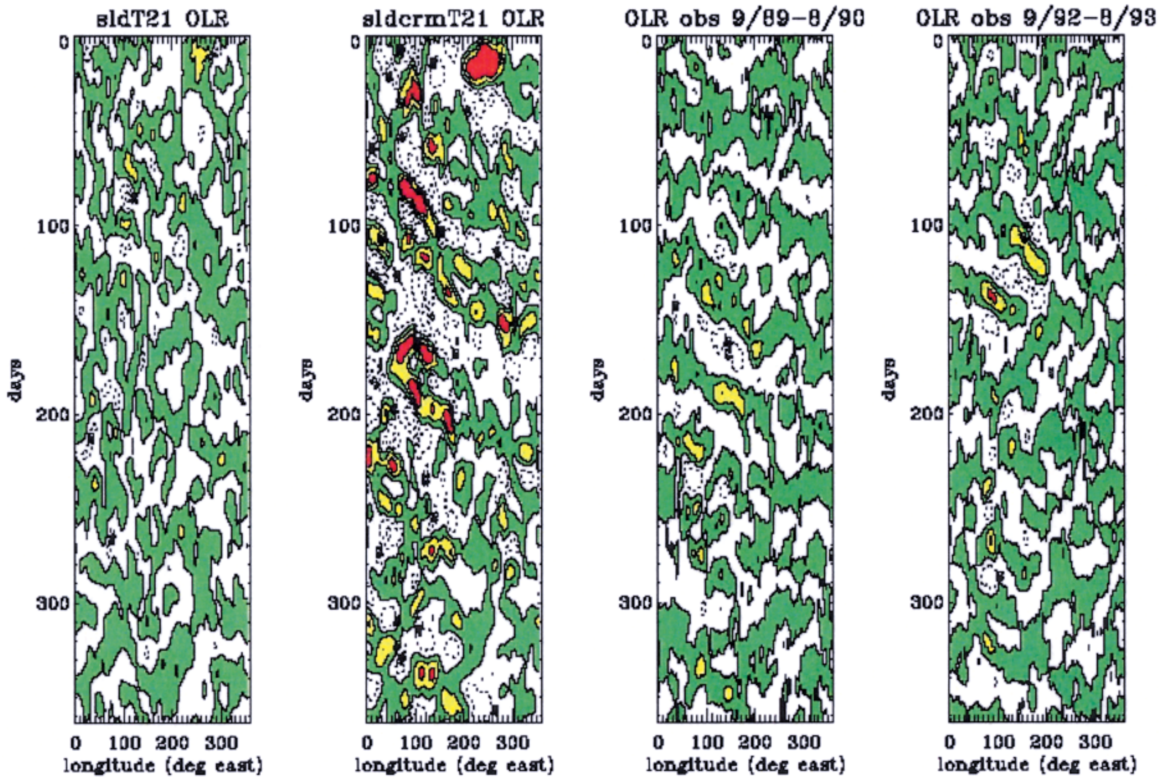


**Fig. 14. Hövmöller diagrams for the equatorial OLR. The left panel shows results from a control run with the CAM. The second panel shows results obtained with the superparameterization. The third and fourth panels show observations for two different periods of time.**

- Super-GCMs explicitly simulate cloud overlap in the microphysical sense.
- Super-GCMs explicitly simulate the convective enhancement of the surface fluxes.
- Super-GCMs explicitly simulate the spatial distribution of precipitation intensity, which is important for determining runoff rates (e.g., prediction of flash floods), etc.
- Super-GCMs may make it possible to explicitly simulate multidimensional cloud–radiation effects.
- Super-GCMs explicitly simulate convectively generated gravity waves.
- A super-GCM can provide global simulations of the statistics of mesoscale and microscale cloud organization, which can then be compared with observations compiled by the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer 1999), and also with new and emerging platforms such as the Tropical Rainfall Measuring Mission (TRMM; available online at http://trmm.gsfc.nasa.gov/; Simpson et al. 1996), the Moderate Resolution Imaging Spectroradiometer (MODIS; available online at http://modis.gsfc.nasa.gov/), the experimental satellite CloudSat (http://cloudsat.atmos.colostate.edu/; Stephens et al. 2002), the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO; available online at www-calipso.larc.nas.gov/), and Global Precipitation Measurement (GPM; available online at http://gpm.gsfc.nasa.gov/).
- Following from the previous point, a super-GCM can *assimilate* cloud statistics based on high-resolution observations. Data assimilation is achieved by comparison of observations with simulations (Charney et al. 1969; Parrish et al. 1997; Atlas 1997; Eyre 1997). Because superparameterizations make it possible for global atmospheric models to simulate the mesoscale and microscale structures of cloud systems, they also make it possible to assimilate observations of the mesoscale and microscale structures of cloud systems into global atmospheric models. Recently, a new project called the Climate Change Prediction Program (CCPP)–Atmospheric Radiation Measurements Program (ARM) Parameterization Testbed (CAPT; available online at www-pcmdi.llnl.gov/capt/) has begun using data assimilation and numerical weather prediction as tools to identify deficiencies of climate models. The super-CAM will be tested by CAPT.

The discussion above shows that a *superparameterization provides a framework for coupling processes together.* Specifically, a superparameterization can couple large-scale dynamics, cloud dynamics, gravity wave dynamics, turbulence dynamics, microphysics, radiative transfer, and atmospheric chemistry, all at the native space and time scales of the clouds. At present, we have nothing remotely close to such a coupling framework for use with conventional parameterizations.

*Computational cost.* We now turn to the obvious and important question of computational cost.

First, the bad news: In the study of KR, the embedded CSRM slowed down the CAM by a factor of 180. When the calculations were done during the winter of 2000, a 1-day simulation with a T42 super-CAM took about 1 h on 64 processors of an IBM SP. This number arose as follows: In the winter of 2000, one copy of the CSRM took about 30 s per simulated day on one processor. Because we were using 64 processors with the T42 super-CAM, we had to run about 100 copies of the CSRM per processor. Therefore, the model used about 1 h of wall-clock time per simulated day. The run time for the host GCM itself was negligible.

Now, the good news: Although a super-GCM is between $10^2$ and $10^3$ times more expensive than the same GCM with conventional parameterizations, this should be compared to the cost of a global CSRM, which, as discussed earlier, is about $10^6$ times more expensive than a current climate model.

On today's computers, the super-CAM implemented by KR would take an unacceptably large amount of wall-clock time to simulate a century. As discussed later, however, faster hardware and revised programming methods have already led to a useful speed-up of the super-CAM, relative to our first experience three years ago. A key point is that massive parallelism has the potential to permit much faster simulations, even on today's computers. Because the CSRMs indifferent grid columns do not communicate, superparameterizations are "perfectly parallel." The wall-clock time can be almost independent of the GCM's resolution so long as we can make the number of processors a constant times the number of grid columns. Embedded CSRMs, thus, provide a way to utilize more processors for a given GCM resolution—we beat Amdahl's Law by making the problem (a lot) bigger.

In short, it is marginally feasible to run climate change simulations using a super-GCM on today's most powerful machines. The cost of such a simulation is not out of line with the importance of the climate change problem. Ten years ago superparameterizations could not have been used because of their computational cost. Today they can be tested in relatively short simulations, given a large resource allocation on one of our most powerful machines. By 2010 superparameterizations will be a very practical approach in some applications.

As computing power increases, we must decide how to use it. One approach is to increase the resolution of our GCMs. This is undoubtedly useful and should be done and is being done, but,

- although increased resolution almost automatically gives better weather forecasts, it does not automatically give more realistic climate simulations, because the results of a climate simulation depend very strongly on incomplete and uncertain parameterizations; and,
- especially with $O$(10–100 km) grid spacing, the "required" parameterizations strongly depend, in poorly understood ways, on the arbitrarily specified grid size (Jung and Arakawa 2003).

A second approach is to replace conventional parameterizations with superparameterizations. This has the potential to provide more realistic simulations of key feedbacks, and, as discussed below, can enable convergence of a global CSRM.

*A continuing role for conventional cloud parameterizations.* Regardless of the future utility of superparameterizations, there will be multiple important and never-ending roles for conventional parameterizations. Obviously, conventional parameterizations will still be used wherever very large computing resources are not available. Conventional parameterizations will still be needed for very long simulations,

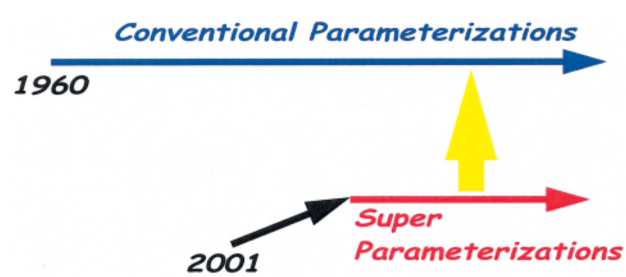


**FIG. 15. Starting now, parameterization development will proceed along two parallel paths: the conventional approach, and the superparameterization approach. The yellow arrow represents the possibility that superparameterizations can help us to learn how to make better conventional parameterizations.**

for example, of Milankovich cycles. Finally, and most importantly, conventional parameterizations will still be needed as "encapsulations" of our (gradually improving) understanding of how clouds interact with the large-scale circulation. We, therefore, envision that, as summarized in Fig. 15, we are entering a new era in which conventional parameterizations and superparameterizations will be developed and applied in parallel. A key point is that conventional parameterizations can be improved more rapidly by taking advantage of what we learn by using superparameterizations.

*Improving the superparameterization.* Despite the apparent promise of superparameterizations, there are major issues that have not yet been addressed.

PROCESSES THAT ARE NOT EXPLICITLY REPRESENTED WITH SUPERPARAMETERIZATIONS. Microphysical processes, involving tiny drops, crystals, and aerosols, must of course be parameterized in both conventional cloud parameterizations and superparameterizations. *An improved microphysics parameterization can give improved results in a climate simulation only if the input of the microphysics parameterization is correct.* Conventional parameterizations provide only gross statistics on such things as cloud dynamics and cloud–radiation interactions. Superparameterizations permit more realistic simulations of these processes, which strongly control cloud formation and dissipation. For this reason, improved microphysics parameterizations are much more straightforward to implement and much more likely to give improved climate simulations when they are linked with superparameterizations.

## COMPUTATIONAL ISSUES

**Super-GCMs are completely new kinds of models. They represent a "mix" of the GCM and the CSRM that raises computational issues, as well as physical issues.**

**As mentioned earlier, it appears that super-GCMs have the potential to make efficient use of very large computers with a thousand or more processors (Fig. SB1), even with relatively modest resolutions for the large-scale dynamics. Table SB1 illustrates this point with a few numbers. The table shows the relative wall-clock time requirements for a unit calculation (e.g., a simulated year) with the CAM, running on 1, 32, and 1024 processors. The computation time is broken down into that used by the "dynamics," which refers to the large-scale dynamical processes; the "physics," which refers to the parameterized physical processes; and the "total," that is, the sum of the dynamics and physics. We assume for simplicity that for the conventional CAM, the dynamics and physics consume equal amounts of wall-clock time on a single processor, that is, one unit each, so that the total wall-clock time required for a unit calculation on a single processor is two units. With 32 processors, both the dynamics and the physics of the conventional CAM speed up by a factor of 30, which is pretty good. For 1024 processors, however, the table shows no further speedup. (In reality there would be a modest further speedup.)**

**For the current super-CAM running on one processor, still at T42 resolution, the wall-clock time used by the physics increases by a factor of 360 relative to the conventional model, while the wall-clock time used by the dynamics is unchanged. The total wall-clock time, thus, increases to 361 units, that is, 180 times more than the conventional model. With 32 processors, both the dynamics and the physics speed up by a factor of 30. Moving from 32 to 1024 processors, there is no significant further speedup of the current super-CAM. As mentioned earlier, this is an artifact of the programming architecture of the current CAM, which prevents the computation from being split into more than 64 parts when the resolution used is T42.**

**FIG. SB1. The Earth Simulator machine of the Frontier Research Project. The machine is located in Yokohama, Japan. Its measured performance is 35.61 Tflops. It consists of 640 nodes that are connected by a high-speed network. Each node contains eight vector processors with 16 GB of memory, for a total of 5120 processors and 10 TB of memory. The Earth Simulator is capable of running a super-GCM fast enough to enable practical climate change simulations.**

Similarly, radiative transfer must still be parameterized with a superparameterization. As mentioned earlier, however, the single most important factor limiting the accuracy of radiative fluxes in GCMs is the deficient input to the parameterization, especially as it relates to clouds. Because cloud formation and cloud overlap are, to a large extent, explicitly resolved by CSRMs, the input to a radiative transfer parameterization can be more realistic with superparameterizations. This is in fact a major advantage of superparameterizations relative to conventional parameterizations.

Turbulence, stratocumulus clouds, and shallow cumuli must still be parameterized with a superparameterization, because the relevant dynamical processes are not resolved by CSRMs. We need new methods to parameterize turbulence and shallow convection in CSRMs, for application in the context of superparameterizations. Again, an explicit simulation of large clouds and mesoscale circulations makes it possible to provide more realistic and detailed input to turbulence and shallow convection parameterizations.

IMPORTANT TECHNICAL ISSUES. *EVERYWHERE ALL THE TIME?* Is it necessary to run the superparameterization in all grid columns of the GCM, on all time steps? An obvious possibility is that the superparameterization could be switched off "when not needed." We believe, however, that it is best to use the superparameterization throughout the entire simulated atmosphere, and on all time steps, for several reasons. First, this is the simplest thing to do, and simplicity is good. Second, efficient parallelization is facilitated by applying the superparameterization in a geographically homo-

**The CAM has recently been reprogrammed at the Oak Ridge National Laboratory so that the physics, but not the dynamics, can use more processors. The new version of the model became available while this paper was under review. We have now transplanted the superparameterization to this new version of the CAM. Actual tests have shown excellent parallel scaling up to 256 processors, still at T42. We expect that good scalability will continue up to 1024 processors, as shown in the last three columns of Table SB1, and we intend to demonstrate this in the near future. At T42 resolution with 1024 processors, each processor will "own" roughly 10 copies of the CSRM.**

**Although we are optimistic that a super-GCM can make efficient use of a massively parallel machine, there are of course a number of questions that remain to be addressed:**

- **To what extent is interprocessor communication a bottleneck with a super-GCM that uses the quasi-3D approach?**
- **What are the memory requirements of super-GCMs, and how do they affect scalability?**
- **What are the software engineering issues associated with super-GCMs?**
- **To what extent is the volume of data ingested an issue for data assimilation with super-GCMs?**
- **What is the best way to record the simulation obtained with a super-GCM? Is it practical to write out the high-resolution cloud fields simulated by the CSRM in each GCM grid cell?**
- **How can we couple a super-GCM with an ocean model, a land surface model, and a sea ice model? Will the coupling represent a computational bottleneck?**
- **Can the superparameterization approach be useful for ocean modeling?**

**These and other computational issues will have to be explored in the years ahead.**

**TABLE SB1. The relative wall-clock time requirements for a unit calculation, with various numbers of processors, for three different GCM configurations. These are rough numbers intended only to illustrate the concept that a highly scalable superparameterization can yield a highly scalable super-GCM.**

| Number of processors | Conventional T42 CAM | | | Super-CAM circa 2000 | | | Near-future super-GCM | | |
|---|---|---|---|---|---|---|---|---|---|
| | Physics | Dynamics | Total | Physics | Dynamics | Total | Physics | Dynamics | Total |
| 1 | 1 | 1 | 2 | 360 | 1 | 361 | 360 | 1 | 361 |
| 32 | 1/30 | 1/30 | 1/15 | 12 | 1/30 | 12 | 12 | 1/30 | 12 |
| 1024 | 1/30 | 1/30 | 1/15 | 12 | 1/30 | 12 | 1/2 | 1/100 | 1/2 |

geneous way. Finally, superparameterizations can give very useful information on such things as cloud fraction and cloud overlap even for routine, undisturbed weather regimes. The utility of superparameterizations is not limited to outbreaks of deep convection. Only "severe clear" conditions make superparameterizations superfluous.

We note, however, that it would be possible to reduce the computational cost of a superparameterization by grouping together a set of neighboring GCM grid columns, and running a single copy of the CSRM to represent the cloud systems over the combined group of columns. A similar approach is sometimes used with radiative transfer parameterizations (e.g., Morcrette 2000). The trade-offs involved with such an approach should be explored.

*Resolution and domain size of the CSRM.* Grabowski has experimented with grid sizes on the order of 2–4 km, while KR have used a grid size of 4 km. Additional research is needed to select the best trade-off between resolution and expense.

*Consistency between the GCM and the CSRM.* Ideally the equations used by the GCM should be the same as those used by the CSRM. For example, the two models should use the same formulation of moist thermodynamics. The CSRM is necessarily nonhydrostatic, so it fits most naturally with a nonhydrostatic GCM, as already used by Grabowski and Smolarkiewicz (1999). Ideally, the GCM and the CSRM should use the same vertical coordinate system, the same vertical resolution, and the same finite-difference schemes. This is all quite do-able, but it has not been done yet.

*Communications between the GCM and the CSRM.* What is the best way to communicate to the CSRM what the GCM-resolved circulations are doing? What is the best way to provide feedback from the embedded CSMR to the GCM? We have used simple approaches up to now, but this issue needs a lot of additional study. Experiments with less expensive regional models can provide guidance here. Research along these lines is currently ongoing at UCLA.

*Lateral boundary conditions of the CSRM.* As discussed earlier, our studies up to now have used periodic lateral boundary conditions. J.-H. Jung and A. Arakawa (2002, unpublished manuscript) have shown that for deep convective regimes this approach produces unacceptable errors when the GCM grid cells are smaller than about 100 km, although it may be acceptable with larger GCM grid cells and for different weather regimes. Even apart from this difficulty, we would like to permit CSRM-simulated squall lines to propagate in a natural way from one GCM grid column to the next, for example, from the Rocky Mountain region to the east coast of North America, which cannot happen with periodic boundary conditions. An alternative approach is discussed below.

*Lower boundary conditions.* The properties of the earth's surface are of course spatially variable on scales resolved by the CSRM. How can information about the high-resolution spatial variability of the lower boundary be used in a superparameterization?

*Orientation and dimensionality of the CSRM.* Is a 2D CSRM acceptable, or do we have to go to 3D? If we use 2D, how should we choose the orientation of the 2D model?

*Convergence to a global CSRM.* Suppose that we have a super-GCM, and that over time, as computing power increases, we refine the mesh of the GCM until eventually it coincides with the mesh of the embedded CSRM. In that limit, the super-GCM should smoothly and naturally "converge," in the mathematical sense, to a global CSRM. Convergence is a logically necessary requirement for any discrete model, but one that has understandably not received much attention from the global modeling community until now, because of the historically low resolution of GCMs. No existing GCM converges to a global CSRM, because no existing GCM includes a parameterization suite that is formulated so as to take account of the model's grid size. At present, no one knows how to build a conventional parameterization of this type. If we *require* convergence to a global CSRM, this requirement can be used as a guiding principle for the design of the next-generation superparameterization.

The plot thickens. Recently, A. Arakawa, an author of this paper, has suggested a new approach to superparameterization that can address most of the issues listed above. The concept will be explained in detail in a forthcoming paper by Arakawa. To begin by putting the idea in context, Fig. 16 summarizes the approach that has been followed up to now. The black squares represent an array of GCM grid boxes, and the red lines represent embedded 2D CSRMs. The CSRM domains do not extend to the edges of the GCM grid boxes. The lateral boundary conditions in the CSRMs are periodic. At the black dots, the GCM and the domain averages of the CSRMs interact.

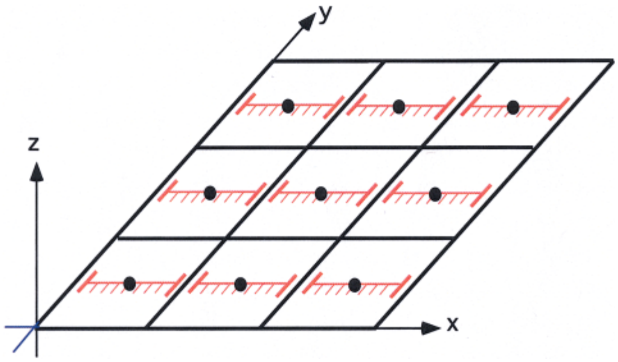


**Fig. 16. The black squares represent an array of GCM grid boxes, and the red lines represent embedded two-dimensional CSRMs. The CSRM domains do not extend to the edges of the GCM grid boxes. The lateral boundary conditions on the CSRMs are periodic. At the black dots, the GCM and the domain average of the CSRM interact.**

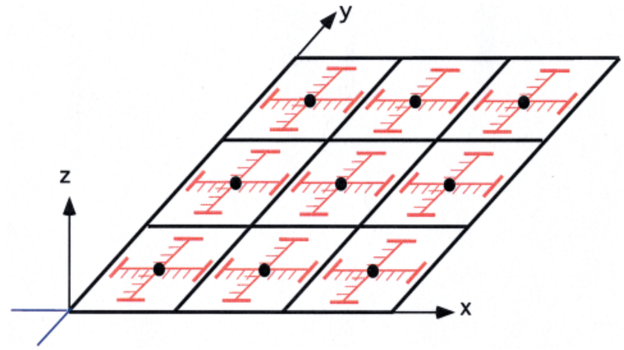


**Fig. 17. An evolved version of the original superparameterization concept depicted in Fig. 16. Two CSRMs are embedded in each GCM grid box. They are oriented at right angles to each other. They have periodic boundary conditions, as before. At the point where the two high-resolution grids overlap, the CSRM is three-dimensional. Elsewhere, it is two-dimensional.**

Figure 17 depicts an important change: We modify the CSRM by adding a second high-resolution grid, oriented at right angles to the first. The two high-resolution grids intersect at a single point within each GCM grid cell. At their intersections, horizontal advective fluxes can be represented as vectors in the horizontal plane. Similarly, at the interaction points only, the horizontal pressure gradient force can be represented as a vector in the horizontal plane. Therefore, at the intersection points only, the CSRM is a three-dimensional model. Elsewhere, it is two-dimensional.

The next step is shown in Fig. 18. Here, the two orthogonal high-resolution grids are extended to the walls of the GCM grid cells. The periodic boundary conditions are replaced by a direct coupling of the CSRMs in neighboring GCM cells. This means that it is now possible for a simulated cloud system, for example, a squall line, to propagate from one GCM grid cell to the next.

For a CSRM grid point that is not at the intersection of the two high-resolution grids, we can do a "quasi-three-dimensional" calculation by interpolation between the neighboring orthogonal high-resolution grids.

As the grid of the GCM is refined, keeping the same resolution for the CSRM grid, the number of CSRM cells in each GCM grid cells is simply reduced, although of course the total number of CSRM grid cells over the globe increases. In the limit, there is a single CSRM grid cell in each GCM grid box, and we have a global (three-dimensional) CSRM. In this way, convergence is achieved.

Following the quasi-3D approach outlined above, the embedded CSRM essentially replaces the GCM as far as the thermodynamic fields (including mass) are concerned. The GCM's dynamical core lives on, however, through the *large-scale* wind fields, which continue to be predicted on the coarse GCM grid. The CSRM predicts the small-scale structure of the wind field on its high-resolution grid. The horizontal winds predicted by the CSRM are "nudged" toward the large-scale winds predicted by the GCM. The nudging of the winds is a "forcing" that permits the CSRM to feel the large-scale dynamics. The strength of the nudging must be chosen such that the forcing is effective, but not so strong that cloud-scale disturbances are trapped within GCM grid cells.

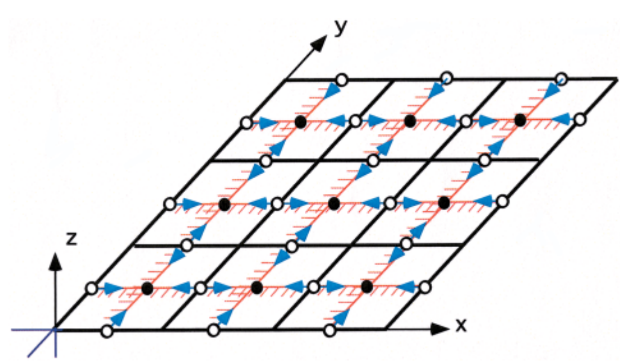


**Fig. 18. Here the two orthogonal high-resolution grids are extended to the walls of the GCM grid cells. The periodic boundary conditions are replaced by a direct coupling of the CSRMs in neighboring GCM cells, as depicted by the blue arrows. The open circles represent points at which the large-scale winds are predicted. At a CSRM grid point that is not at the intersection of the two high-resolution grids, we can do a quasi-three-dimensional calculation by interpolation between the neighboring orthogonal high-resolution grids.**

The quasi-3D approach represents a major advance over the 2D approach that has been followed up to now, for the following reasons:

- Two-dimensional is replaced by quasi-3D.
- The orientation problem goes away.
- Convective systems can propagate from one GCM grid column to the next.
- There is no reason to alter the formulation of the embedded CSRM when the GCM's resolution is increased. In this sense, the superparameterization is "resolution independent."
- Realistic topographic boundary conditions can be prescribed from data, and used to generate orographic gravity waves and orographic clouds, so that orographic gravity wave drag can be included in the framework of the superparameterization.
- A GCM with a quasi-3D superparameterization *converges* in a smooth and natural way to a global CSRM, as the resolution of the GCM is refined.

At the same time, it should be pointed out that the quasi-3D approach requires more computation than the 2D approach. In addition, models using the quasi-3D approach will be somewhat more difficult to parallelize because of the need for communication among processors running coupled subdomains of the embedded CSRM.

**WHERE DO WE GO FROM HERE?** We have argued that the quasi-3D approach to superparameterization will play a key role in future climate simulations. We do not claim, however, that superparameterizations will solve all of our problems. Despite the strengths of the new approach, our supersimulations will fall short of reality in ways that will frustrate and challenge us. When problems do arise, however, superparameterizations will permit us to diagnose and attack them in terms of the cloud-scale physical processes that are directly simulated by CSRMs. These are processes that we understand relatively well—certainly much better than we understand the statistical cloud dynamics contemplated in the context of conventional parameterizations. In addition, cloud-scale physical processes can be observed in detail through field experiments. We will still have problems, but we will have a better chance of solving them.

Superparameterization research is poised to proceed in many directions at once. It must, therefore, involve many projects, many teams of investigators, and many institutions. As follows, some of the primary research directions can be anticipated:

- First, we must explore more fully the capabilities of the superparameterization already implemented in the CAM. This involves exploiting our new capability, and at the same time mapping out the physical and computational limits of that capability. This work is ongoing, but it can go faster if there are more participants.
- Second, we must work to develop improved superparameterization methods, following the quasi-3D approach outlined earlier, and taking advantage of additional ideas as they come. This will involve making changes in both the CSRM and the host GCM, as outlined below. It will also involve tests of ideas in regional-scale models.
- Third, we must apply superparameterizations to the simulation of anthropogenic climate change. This will require a quantum jump in the computation power available for climate change simulations.
- Finally, we should move superparameterizations into the domain of weather analysis and forecasting, including numerical weather prediction with both global and regional models.

Some of these tasks can be "managed" within technology projects that are supported with line-item funding. Others fall under the heading of pure research and should be supported through the usual peer-reviewed proposal-and-grant process.

This article is, quite obviously, an "advocacy piece." It is intended not only to inform, but also to persuade. We have tried to make the case that the use of superparameterizations for climate simulation offers a huge payoff, although at a very high computational price. We believe that superparameterizations are the only way to break the cloud parameterization deadlock. The emergence of superparameterizations presents an opportunity for our community to undertake a "Manhattan Project" for cloud parameterization.

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