CONFRONTING MODELS WITH DATA

The GEWEX Cloud Systems Study

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A group of cloud modelers and global modelers has gradually learned how to make the most of the available observations.

The use of data to evaluate models is fundamental to science. Ideally, evaluations can be controlled and optimized in the laboratory; in most cases, however, atmospheric scientists have to perform model–data intercomparisons by taking advantage of the uncontrolled opportunities that nature provides. A model-evaluation project is complicated in at least two distinct ways. The technical complexities are obvious and daunting: Data must be collected and analyzed, models must be developed and run, and the two sets of numbers must be brought into meaningful juxtaposition. This is hard enough. An additional and equally complex task, however, is to foster communication and fruitful interactions among the diverse scientific communities whose cooperation and combined expertise are needed in order to carry out the technical work.

The Global Energy and Water Cycle Experiment (GEWEX) Cloud System Study (GCSS) is a case in point. GCSS was organized in the early 1990s by K. Browning and colleagues (Browning et al. 1993, 1994). The challenges that arise as GCSS brings observations and models together are a microcosm of challenges that face all of atmospheric science. Over a period of years, GCSS has devised what we call the "GCSS process" a mode of operation that appears to optimize its scientific productivity. The GCSS process was devised partly through trial and error and partly through introspection. The primary purpose of this article is to outline the key elements of the GCSS pro-

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cess, which, we believe, have the potential to be useful for many atmospheric science projects.

The goal of GCSS is to facilitate the development and testing of improved cloud parameterizations for climate and numerical weather prediction (NWP) models. GCSS deals with collections of clouds acting as systems, spanning a range of scales. Browning et al. (1993, 1994) envisioned that the development of improved cloud parameterizations could be aided by the use of *cloud-system-resolving models* (CSRMs). These are models with sufficient spatial and temporal resolution to represent individual cloud elements, and covering a wide enough range of time and space scales to permit statistical analysis of simulated cloud *systems.* As envisioned by Browning et al., CSRMs can be used as experimental test beds to develop understanding, to produce synthetic four-dimensional datasets, and to test parameterizations.

Despite their high computational cost, CSRMs do not simulate cloud systems from first principles. Although the cloud-scale and mesoscale *dynamical* processes, which must be parameterized in atmospheric general circulation models (GCMs), are explicitly simulated in CSRMs on scales down to a kilometer or so in the horizontal and 100 m or so in the vertical, the important microphysical, turbulent, and radiative processes are still parameterized. Because CSRMs explicitly represent mesoscale and cloud-scale dynamical processes, many of the scientists engaged in CSRM-based research are mesoscale and/or cloud-scale dynamicists. CSRM research has also been taken up by microphysics modelers, because the detailed simulations of cloud dynamics provide the input needed by detailed microphysical models.

A second important thread of GCSS research is centered around the use of single-column models (SCMs). As the name suggests, an SCM is essentially the column physics of a GCM, considered in isolation from the rest of the GCM; that is, *an SCM is that which the GCSS process aims to test and improve.* The key utility of SCMs is that they can be used to make connections between GCMs and data collected in the field, thus facilitating observationally based evaluations of new and supposedly improved parameterizations, in isolation from the large-scale dynamical framework of a GCM. Over the past several years we have seen the creation of SCMs in most of the global modeling centers around the world, including both climate modeling centers and NWP centers. Historically, the scientists who work with SCMs have tended to be members of the large-scale modeling community. Today this is changing; as a result of the efforts of GCSS, a number of cloud modelers have begun doing parameterization development using SCMs.

Both a CSRM and an SCM can be considered to represent a GCM grid column. To drive these models with data, we must first accurately measure the large-scale meteorological processes that are acting on a column of the atmosphere, including the time-varying profiles of the large-scale advective tendencies of mass, temperature, water vapor, and (ideally) cloud water and ice. This is very difficult to do, even after several decades of experience, even with the

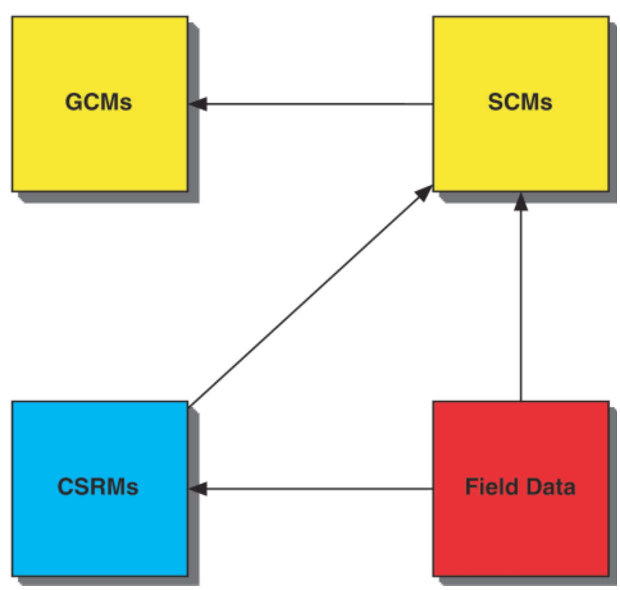


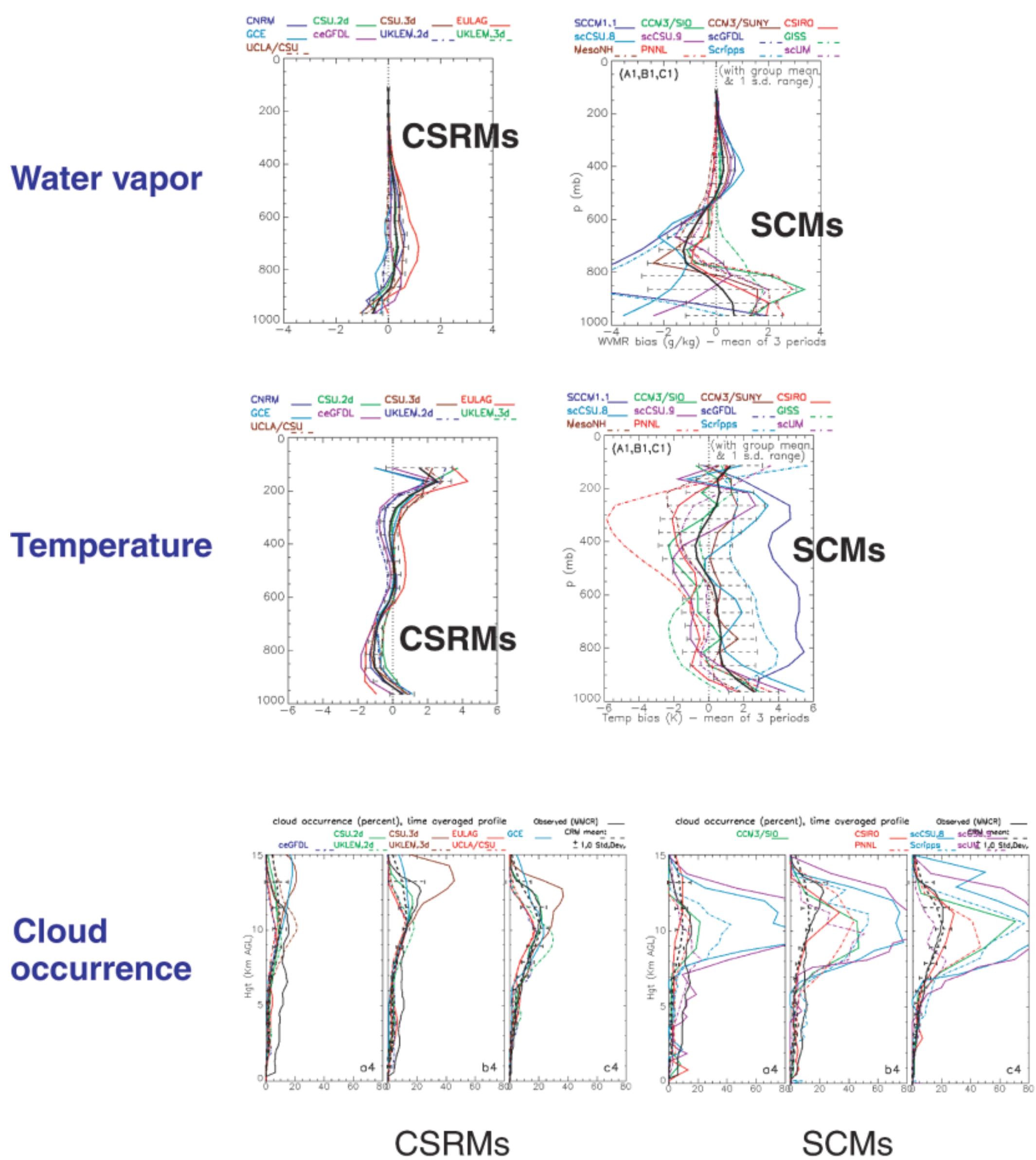
Fig. 1 (right). Diagram illustrating how a CSRM and an SCM can be combined with field data to develop improved parameterizations for GCMs. The arrows in the figure show the "flow of information." This flow starts with the field data, in the lower right-hand corner of the figure. The observations collected are used with both the CSRM and the SCM, in essentially the same three ways for both models. First, both models are initialized from observations. Second, both are "driven" with the observations of, e.g., large-scale vertical motion. Finally, the results that the two models produce, in response to this observed forcing, are compared against other observations collected in the field, e.g., observations of cloudiness and surface radiation. Through data assimilation, field data also can be directly used by GCMs, although that is not part of the SCM approach. This figure is adapted from Randall et al. (1996).

Fig. 2 (facing page). A comparison of CSRM and SCM results for water vapor, temperature, and cloud occurrence, based on data collected at the ARM SGP site. For water vapor and temperature, we show errors relative to observations for a single multiweek observing period. For cloud occurrence, we show results of the observed (via cloud radar) and simulated cloud occurrence as a function of height, for three shorter periods. The CSRMs collectively perform better than the SCMs. The same is true in additional case studies based on TOGA COARE and other datasets (not shown).

rapid advances in observing systems, and even in data-rich regions such as central North America [see, e.g., the study of Zhang et al. (2001)]. Once the observed large-scale dynamical processes have been quantified, they can be used to "force" the CSRMs and SCMs, which then simulate the cloud-formation and radiative-transfer processes inside the column. Finally, additional observations are used to evaluate the results produced by the models. This strategy is illustrated in Fig. 1.

CSRMs compute many quantities that are very difficult to observe, such as the four-dimensional distributions of liquid water and ice. Although this simulated information is not a substitute for real observations, because as mentioned above CSRMs contain parameterizations that introduce major uncertainties, CSRM results can, nevertheless, be judiciously compared with SCM results in order to diagnose problems with the latter. Finally, a parameterization tested in an SCM can be transferred directly to a three-dimensional GCM. Further discussion of SCMs, including their important limitations, is given by Randall et al. (1996).

A key premise of the research strategy outlined above is that CSRMs give more realistic simulations than SCMs. This is to be expected, because CSRMs explicitly represent many processes that SCMs can only incorporate in a statistical manner, through various closure assumptions. Nevertheless, as noted by Browning et al. (1994), it is important to confirm the anticipated superiority of CSRM results relative to SCM results. GCSS has accomplished this, through various case studies. Examples are shown in Figs. 2



and 3. Measurements by the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) program millimeter cloud radar (MMCR) in Oklahoma provided observed profiles of hydrometeor (cloud plus precipitation) fraction. Figure 2 shows that most of the CSRM-simulated water vapor, temperature, and cloud fraction profiles are in reasonable agreement with the observations, while the SCM results are much worse in most if not all cases. Figure 3 compares the cloud fraction profiles for the entire 29-day period, as observed by the MMCR, simulated by the University of California, Los Angeles–Colorado State University (UCLA–CSU) CSRM, and simulated by the National Centers for Environmental Prediction (NCEP) SCM (based on the NCEP global model). Even with a flawless model and 3-h time averaging, we should not expect perfect agreement of the simulated cloud fraction averaged over the large-scale CSRM–SCM domain (with a diameter of 300 km) with the cloud fraction observed by the cloud radar (at a point). Nevertheless, the CSRM cloud fraction is in good agreement with the observations, except on the first day, and around the middle of the simulation when a clear period was observed.

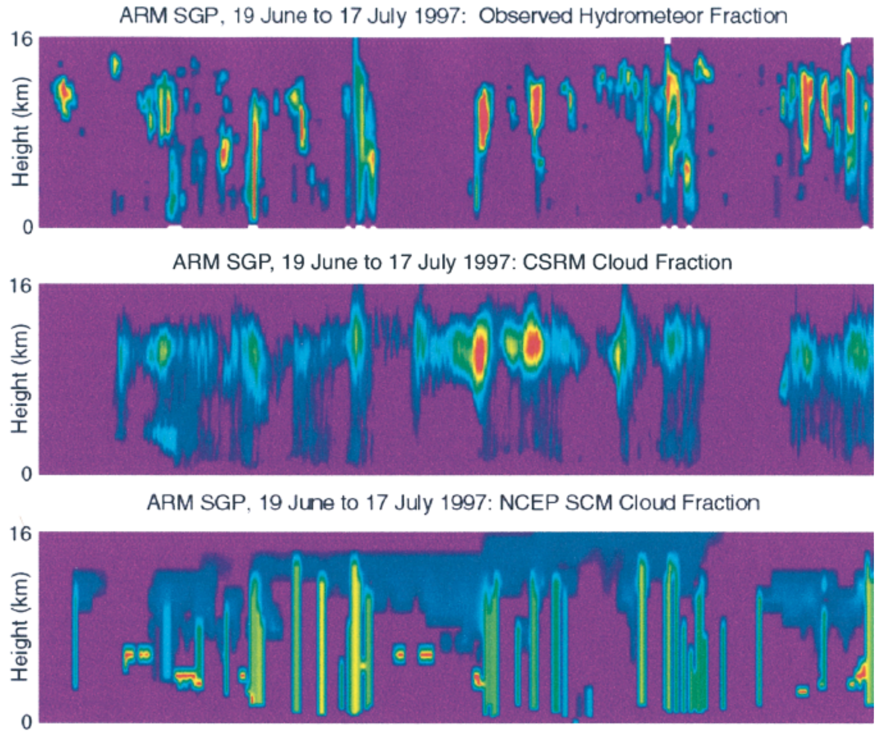


Fig. 3. Time–height cloud fraction for WG4 case 3, surface to 16 km: (top) observed by MMCR (3-h averages), (middle) simulated by UCLA–CSU CSRM (1-h averages), and (bottom) simulated by NCEP SCM (3-h averages). Color indicates cloud fraction, which ranges from 0 (violet) to 1 (red).

We consider it likely that the largest differences between the CSRM results and the observations are primarily due to errors in the prescribed large-scale advective tendencies, rather than to deficiencies of the CSRM's physics. There are significant differences between the NCEP SCM and observed cloud fraction profiles, most notably in the SCM's underestimate of cloud fraction at high levels. The NCEP SCM diagnoses the stratiform cloud fraction as a function of the relative humidity, and the convective cloud fraction according to the intensity of the convection.[1] The total cloud fraction equals the convective cloud fraction if present; otherwise, it equals the stratiform cloud fraction. The 3-h averaged surface rainfall rates, liquid water paths, and precipitable water amounts from the CSRMs are in significantly better agreement with the observations than are the corresponding results from the SCMs.

The work outlined above was carried out through what we call the *GCSS Process Mark 1*, which is schematically depicted in Fig. 4. The diagram shows three communities of scientists, represented by the rectangular boxes; these are "data collection community," the "CSRM community," and the "GCM–SCM community." In order for GCSS to accomplish its goals, these three groups have to work together.

Such cooperation must be fostered and encouraged because of "cultural differences" among the communities, including differences in scientific background, interests, goals, and thought processes. These cultural differences make it difficult for the communities to interact, and this difficulty slows the progress of our science. We view GCSS as a "melting pot" for engendering such transcultural interactions.

The flow of information in the GCSS Process Mark 1 is indicated by the arrows in Fig. 4. Data are

[1] The cloud parameterization in the NCEP global model has changed while this paper was under review. The current version of the model diagnoses stratiform cloud fraction from the cloud water–ice mixing ratio, which is now a prognostic variable.

collected in various field programs and provided to the CSRM community. The CSRM community uses the data to "certify" the CSRMs as reliable tools for the simulation of a particular cloud regime. It then uses its models to develop parameterizations, which are provided to the GCM/SCM community.

As GCSS evolved, we came to the conclusion that the GCSS Process Mark 1 was seriously incomplete and somewhat unrealistic. The experiences that led us to this conclusion are outlined in section 2. A revised approach is explained in section 3, and its results to date are discussed in section 4. Conclusions are provided in section 5.

EXPERIENCES WITH THE GCSS PROCESS MARK 1.

GCSS began with four working groups (WGs), each defined with respect to a particular cloud-system type:

- WG1, which deals with boundary layer clouds including stratocumulus clouds and shallow cumulus clouds;
- WG2, which deals with cirrus clouds;
- WG3, which is focused on extratropical layer cloud systems; and
- WG4, which investigates precipitating deep convective cloud systems.

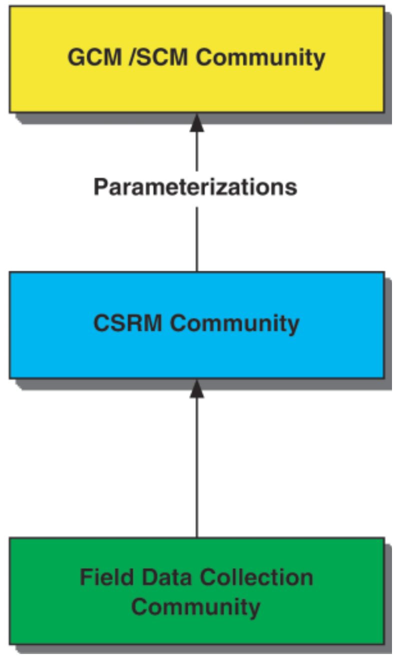


FIG. 4. The GCSS Process Mark 1, as envisioned by Browning et al. (1993, 1994). Data are collected and used to drive CSRMs. Analysis of the CSRM results leads to the development of improved cloud parameterizations, which are then provided to the large-scale modeling community. A revised version of this diagram is given in Fig. 5.

In 1999, an additional WG was created:

- WG5, which deals with polar clouds, recognizing the importance of these clouds for the ice–albedo feedback.

The scientific goals of the five WGs are listed in Table 1. Each of the WGs has been quite active. Their accomplishments (through 2000) were summarized in some detail by Randall et al. (2000), and are only briefly sketched here. Conclusions of interest to the GCM/SCM community are highlighted in Table 2.

WG1 aims to improve physical parameterizations of clouds, other boundary layer processes, and their interactions. The primary approach of WG1 has been to compare observations of cloud-topped boundary layers with simulations produced using SCMs and large eddy simulation (LES) models. Most of the leading groups modeling boundary layer clouds have participated in the WG1 workshops, which have been held on a quasi-annual basis. The WG has focused strongly on entrainment at the tops of stratocumulus clouds and on the sides and tops of shallow cumulus clouds. This focus is justified by the great importance of entrainment for the evolution of boundary layer cloud systems

TABLE 1. Scientific objectives of the five GCSS working groups.

Working group 1 aims to improve physical parameterizations of boundary layer clouds (see online at http://www.amath.washington.edu/~breth/GCSS/GCSS.html.)
What controls the entrainment on the tops of stratocumulus, and on the tops and sides of cumulus?
What are the physical processes that are responsible for the selection of cloud type (Sc vs Cu) and cloud amount?
What are the consequences of cloud properties (micro- and macrophysical) on the cloud radiative properties and the energy balance at the earth's surface and top of the atmosphere?
How are the mesoscale circulations in the cloud-topped boundary layer generated and how does the mesoscale variability interact with other processes such as entrainment, radiation, and drizzle?
Can the dynamics of the PBL be represented by a model that works across PBL regimes, or must different regimes be identified based on external criteria, and then modeled separately?

Table 1. Continued.
Working Group 2 focuses on cirrus clouds (see online at http://eos913c.gsfc.nasa.gov/gcss_wg2/)
What level of microphysical complexity/sophistication is required for adequate treatment of cirrus clouds and their effects in large-scale models (climate and NWP)? A related critical question is the following: What level of microphysical complexity/sophistication is required for adequate treatment of cirrus clouds in remote sensing applications, both space based and surface based?
What vertical resolution is required in large-scale models to enable adequate representation of the large-scale forcing to cirrus cloud formation?
To what extent is the parameterization of cloud dynamical processes and feedbacks (radiation–latent heat–dynamics) required for the treatment of cirrus clouds in large-scale models? Similarly, to what extent must the ambient mesoscale (gravity) wave environment be explicitly taken into account?
What are the effects of the ambient aerosol population on cirrus cloud properties, and do variations in aerosols (or aerosol activation spectra via dynamics) lead to significant variations in cloud properties? How important is heterogeneous nucleation, and when is it important?
Can/should the parameterization of cirrus clouds formed via large-scale ascent in a large-scale model be applied to cirrus formed via detrainment from deep convective cloud systems?
Working Group 3 focuses on midlatitude cloud systems (see online at http://www.msc-smc.ec.gc.ca/GEWEX/GCSS/GCSS_wg3.html.)
How important is it for GCMs to realistically parameterize subgrid-scale mesoscale cloud structure and cloud layering in extratropical cloud systems?
What level of complexity of parameterized microphysical processes is needed in order that weather and climate general circulation models can realistically simulate extratropical cloud systems?
What is the validity of microphysical parameterizations in weather and climate general circulation models for midlatitude cloud systems forced by orography?
Why are climate models deficient in developing clouds in the weakly forced regimes of midlatitude cloud systems?
Why are the components of the water budget associated with midlatitude cloud systems poorly represented in climate simulations?
WG4 deals with deep, precipitating convective cloud systems, which are active over large portions of the Tropics and also during the summer over the midlatitude continents (see online at http://www.met.utah.edu/skrueger/gcss/wg4.html)
The occurrence (frequency and intensity) of deep convection. This includes the diurnal cycle of deep convection over land, and other interactions with the boundary layer.
The production of upper-tropospheric stratiform clouds by deep convection. This includes the issue of microphysical complexity: how much is required in GCMs and NWP models?
Parameterized vs resolved motions as horizontal resolution increases. This is an issue now for mesoscale NWP models and for future global NWP models and GCMs.
Working Group 5 deals with polar clouds (see online at http://paos.colorado.edu/faculty/curry_home/index.html)
How does the phase of lower-tropospheric clouds depend on temperature and aerosol characteristics, and how are mixed-phase clouds maintained?
What is the mechanism that leads to the multiple layering of cloud systems over the Arctic Ocean, and to what extent does this complex vertical cloud structure need to be resolved in GCMs?
To what extent must unusual features of the polar boundary layers (e.g., cloud-top humidity inversions, heterogeneous underlying surface) be represented in GCMs to adequately simulate boundary layer clouds in the polar regions?
How do clouds and their radiative effects influence the physical and optical properties of the snow/ice surface?

(e.g., Bretherton et al. 1999a,b). WG1 has enjoyed fruitful interactions with several large-scale modeling centers, including the European Centre for Medium-Range Weather Forecasts (ECMWF) and the Met Office. These centers have conducted evaluations of parameterizations within the framework of the WG1 case studies (e.g., Lock 1998, 1999; Lock and MacVean 1999; Lock et al. 2000).

WG2 focuses on cirrus clouds. Several state-of-the-art GCMs now explicitly predict the occurrence and amount of ice in cirrus clouds. These parameterizations are difficult to test against the available data; for

TABLE 2. Selected GCSS results that are relevant to global modeling.

Boundary layer cloud systems
Given specified boundary forcing, radiation and large-scale advection, and no precipitation, LES models all simulate shallow cumulus boundary layers (cloud fraction profile, entrainment and detrainment, cloud liquid water, etc.) very similarly, but the same models strongly disagree with each other for the case of stratocumulus clouds under a strong inversion, where entrainment is not resolved.
LES models show that shallow cumulus cloud fields have greater cloud fraction and cloud mass flux at the base of the cloud layer than at the top, and relatively little buoyancy in a typical cloud element. Pre-GCSS parameterizations were almost universally inconsistent with this recent LES result.
In simulations of continental shallow cumulus clouds, LES models all agreed closely on the evolution of the boundary layer thermodynamic profiles and the cloud statistics. In contrast, the SCM results were widely scattered. The shapes of the vertical profiles of LES-simulated cloud fraction, fractional entrainment rate, and detrainment rate are qualitatively similar to those of marine trade cumulus. The clouds are, on average, barely buoyant, and the cloud fraction decreases strongly with height. SCMs often do not reproduce these basic features, and in some cases deepen the shallow cumulus layer much too rapidly.
In simulations of the diurnal cycle of marine stratocumulus clouds, participating LES models showed qualitatively similar behaviors, with daytime cloud thinning, but with intermodel variations in the entrainment rate and consequent evolution of PBL height. SCMs were also able to qualitatively reproduce the diurnal cycle, but with even more variation in the evolution of cloud thickness and entrainment rate. These differences highlight the continuing difficulty of reliably simulating, and parameterizing, stratocumulus entrainment.
Cirrus cloud systems
An idealized cirrus model intercomparison project involving 2D and 3D CSRMs with bin and bulk microphysics, as well as SCMs with bulk microphysics, exhibited large differences in ice water path among the models. These differences were found to be primarily due to the ice fall speed parameterizations.
In idealized CSRM experiments (Köhler 1999), radiation and turbulence were found to have major effects on the lifetimes of cirrus clouds. Because of the upward turbulent flux of water associated with radiatively driven turbulence, optically thick ice clouds decay more slowly than would be expected from microphysical crystal fallout. The upward moisture flux due to turbulence is partially balanced by the downward transport of water by snowfall. Based on these results, Köhler developed an empirical parameterization of the effects of upward turbulent water fluxes in cloud layers by 1) identifying the timescale of conversion of cloud ice to snow as the key parameter, and 2) regressing it onto radiative heating and environmental static stability. His results showed that artificially suppressing the impact of cloud turbulent fluxes reduces the global mean ice water path by a factor of 3, and produces errors in the solar and longwave fluxes at the top of the atmosphere of about 5–6 W m^{-2}. This is consistent with aircraft measurements, which also indicate that neglecting the cloud-scale circulations in cirrus clouds may lead to an underestimation of the grid-averaged ice water content by a factor of 2 (Donner et al. 1997).
Frontal cloud systems
The diabatic effects of sublimation, melting, and evaporation strongly influence prefrontal circulations. In particular, subliming cirrus can serve to trigger prefrontal descent that suppresses midlevel clouds. The models tend to produce the correct cloud types in strongly forced situations but not in weakly forced ones. WG3 has concluded that parameterized fall speeds and evaporation processes are quite important, a conclusion that is consistent with the findings of WG2.
Precipitating convective cloud systems
CSRMs perform significantly better than SCMs in all cloud-related measures, including cloud microphysics, without tuning.
The largest (and most important in terms of precipitation and cloud radiative forcing) convective cloud systems consist of many individual cumulonimbus cells whose high-level outflow forms an extensive high cloud that includes a (stratiform) precipitating part and a nonprecipitating part. In some cases, the convective system is organized into a narrow line of cumulonimbi and an extensive, trailing anvil region. CSRMs can successfully reproduce the structure and evolution of such systems (e.g., Redelsperger et al. 2000a).
The enhancement of surface fluxes by subgrid-scale wind variability (i.e., gustiness) needs to be considered in the parameterization of surface fluxes used in GCMs. There are two different sources of gustiness: deep convection and boundary layer–free convection. For boundary-layer free convection, it is well known that the gustiness is related to the free convection velocity. For deep convection, the dominant source of gustiness are the downdrafts and updrafts generated by convective cells. Results indicate that this gustiness can be related either to the surface precipitation rate or to the updraft and downdraft mass fluxes.
Polar cloud systems
Preliminary conclusions from the clear-sky radiative transfer model intercomparison indicate substantial errors in many of the models in the treatment of the water vapor rotation band. Errors in this treatment are amplified in the Arctic because of the low specific humidity. Because of the low specific humidity and high relative humidity, aerosol forcing in the Arctic is enhanced. Models that do not include aerosols, or specify aerosol composition incorrectly, can incur significant errors.

example, we currently lack global measurements of cloud ice content. A key task of WG2 is to evaluate the validity and/or stimulate the improvement of such parameterizations through application and improvement of theory (models) and data. After several workshops, WG2 now involves the vast majority of research groups concerned with the details of modeling cirrus clouds, with active participation by large-scale modelers and also by key researchers concerned with measurements of cirrus clouds.

WG3 deals with midlatitude frontal cloud systems. The Southern Ocean is blanketed by multilayer cloud systems associated with baroclinic weather systems, while the Northern Hemisphere storm tracks produce the brightest cloud albedos anywhere. In four major case studies, WG3 has made extensive use of regional or "limited area" models (LAMs), which can represent the four-dimensional structure of an extratropical synoptic system (e.g., Ryan et al. 2000). Also, WG3 has made extensive use of satellite data, including data from the International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer 1999). In these two ways, the approach of WG3 has differed considerably from those of the other GCSS WGs.

WG4 deals with deep, precipitating convective cloud systems, which are active over large portions of the Tropics and also during the summer over the midlatitude continents. These cloud systems produce globally significant precipitation, which is associated with convective heating of the troposphere, as well as strong cloud-radiative effects. WG4 has conducted extensive studies based on the Tropical Ocean Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) data (e.g., Bechtold et al. 2000; Redelsperger et al. 2000a), and more recently on ARM data (Xu et al. 2002; Xie et al. 2002).

In January 1999, the GEWEX Scientific Steering Group approved the formation of GCSS Working Group 5, which deals with polar clouds. This action was motivated by our poor understanding of the physical processes at work in the polar cloudy boundary layer; poor simulations of polar cloud, radiation, and boundary layer processes by current GCMs; and the predicted Arctic amplification of greenhouse warming. Several features of the polar climate contribute to the difficulties in simulating the cloud and radiation environment by GCMs. These include an unusual clear-sky radiative-transfer regime characterized by cold temperatures and low humidities, arranged in complex vertical structures including strong inversions; unusual cloud types such as diamond dust, persistent mixed phase clouds, thin multiple cloud layers, and convection from leads in sea ice; and the highly reflective and heterogeneous snow/ice surface. WG5 is presently using data from the First ISCCP Regional Experiment (FIRE) Arctic Clouds Experiment (Curry et al. 2000) and the Surface Heat Budget of the Arctic Ocean (SHEBA; Uttal et al. 2000).

Early GCSS meetings were dominated by mesoscale and microscale dynamicists and microphysicists; there was some but not much participation by the GCM/SCM community. Nevertheless, GCSS has worked hard, from the beginning, to engage the GCM/SCM community. As part of this effort, GCSS conducted a workshop in November 1998, which was hosted by the ECMWF; the proceedings were published by the World Climate Research Programme (2000). The meeting brought together a diverse group of over a hundred scientists with strong common interests, who nevertheless rarely hold joint meetings. The participants included global modelers with an interest in cloud parameterization, mesoscale and microscale cloud modelers, radiative transfer specialists, and remote sensing specialists. The workshop achieved its primary aim of producing a heightened level of communication among the various groups. Perhaps the most important practical benefit of the workshop was the exposure of the global modeling, radiative transfer, and remote sensing communities to the parameterization-testing opportunities offered by the various GCSS WGs. A follow-up workshop took place recently, in May 2002, in Kananaskis, Alberta, Canada.

AN ASSESSMENT, AND MIDCOURSE CORRECTIONS. Broadly speaking, a successful GCSS project has one or more of three outcomes:

- The importance of a cloud process is quantified, for a particular cloud system, thus providing guidance to parameterization efforts.
- Poorly understood but important cloud processes are simulated using a CSRM, thus providing a pathway to scientific understanding.
- A promising new cloud parameterization, developed and/or tested through the activities of a GCSS working group, is adopted for use in a climate model, or an NWP model, or a CSRM.

By the end of 2000, the GCSS Process Mark I had produced results of all three types. Five vibrant WGs were hard at work, generating integrated datasets, and publishing the results of various case studies based on these datasets. SCMs were being used at virtually all global modeling centers. In addition, GCSS had successfully facilitated the development, testing, and applications of some interesting and useful new parameterizations. The 1998 ECMWF workshop brought about successful transcultural interactions among the various participating groups.

Nevertheless, by the end of 2000, GCSS had not yet fully achieved its ambitious goals, for several reasons:

- We still found it difficult to attract a good showing of global modelers to WG meetings, and to gain their participation (with SCMs) in case studies.
- Experience had shown that it was necessary for the GCSS WGs to spend a substantial fraction of their energy on *data integration,* which consists of producing observation-based datasets suitable for use with the CSRMs and SCMs. Data integration was not sufficiently recognized as a major activity in the 1994 science plan, which did, however, envision the "preparation of carefully assembled case study datasets" consisting of model output together with observations. We now appreciate that such datasets are themselves among our most important products, because they are comprehensive and internally consistent portraits of the processes at work in the cloudy atmosphere.
- As a result of the studies performed by the GCSS WGs, it had become clear that synthetic datasets generated using CSRMs and LES models can be used only cautiously as proxies for real data, and only in certain cases and/or for selected variables.
- At first, GCSS did not adequately recognize how important satellite data would be for its work.
- GCSS lacked (and still lacks) sufficient participation by the radiative transfer community. As a result, cloud–radiation interactions were not sufficiently emphasized in GCSS WG studies.
- Our community finds it difficult to cope with five WGs holding annual meetings, plus the annual meetings of the GCSS Science Steering Group and the GEWEX Science Steering Group and the GEWEX Modeling and Prediction Program. Our cup runneth over.

Analogous problems have been encountered elsewhere in the atmospheric sciences.

In 2000, we addressed these issues by developing a revised version of the GCSS process, designed as a "midcourse correction" to improve the scientific productivity of GCSS. The concept is shown in Fig. 5. The key differences from Fig. 4 are the red and blue items. In brief, the existence and key role of a data integration community are now acknowledged, the GCM/SCM community now plays a more active role in the GCSS process, and the importance of satellite data, as well as field data, is now explicitly recognized.

First, consider the data integration activity. Raw data must be integrated in order to yield products that can be used to force models or to initialize models or to evaluate model results. One of the primary tasks of GCSS, from the very beginning, has been to produce such integrated datasets, which are provided to both the CSRM group and the GCM/SCM group. As indicated in Fig. 5, GCSS now addresses the need for such datasets through explicit and partially centralized data integration activities. Just as global modelers ask questions of and receive answers from the CSRM community, both the global modelers and the CSRM community ask questions of the data; that is, they learn by directly confronting their modeling assumptions and their model results with observations. In addition, modelers can uncover problems with the

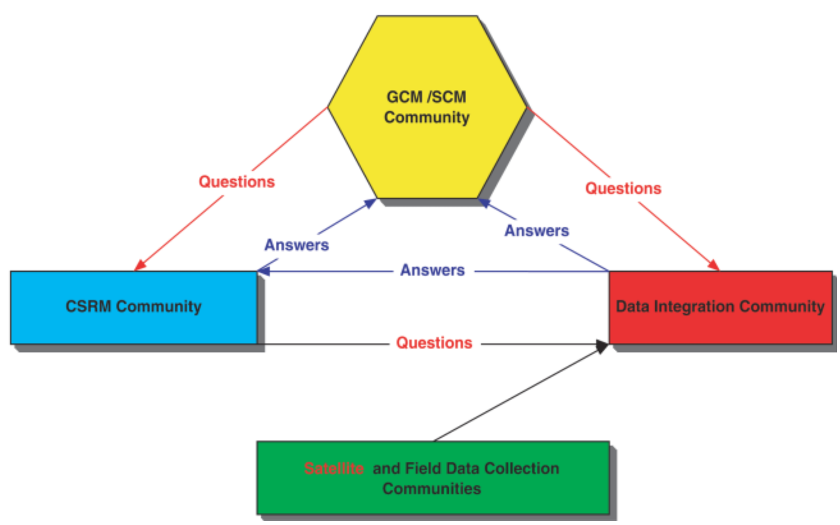


Fig. 5. A revised GCSS process; cf. Fig. 4. The key differences from Fig. 4 are indicated by the red and blue items in the present figure. Satellite data are recognized as having an importance comparable to that of field data. Data integration is now recognized as a key activity distinct from the others. The scientific questions that are posed in the process of parameterization development are now shown to originate within the GCM/SCM community and/or the CSRM community. Answers to these questions are obtained through the use of CSRMs together with data.

observations. For example, modeling studies performed by GCSS WG4 were instrumental in the discovery and correction of problems with the TOGA COARE sonde data.

Certain intrinsic characteristics of the modeling and observing communities make it difficult to bring models and data together. For the most part, observers are content to develop and (sometimes) apply retrieval algorithms to produce a data stream, and feel that their responsibility stops there. Climate modelers want neat, gridded, averaged, and in short "ready-to-eat" geophysical variables presented as data products. They do not want to hear about or think about random errors or sampling biases. They lack the expertise to make meaningful use of raw radiometer data or raw lidar data or raw cloud radar data or raw satellite data or raw sonde data or raw profiler data or raw aircraft data. Moreover, the analysis of raw data is a full-time job, which, if undertaken by the modelers, would preclude timely modeling progress. Data integration is the process by which we bridge this yawning gap between what the data-collection community provides and what the modeling community needs. Data integration consists of bringing together data from disparate instruments, and combining them into a coherent and comprehensive physical description of what was observed, in a form suitable for use in the evaluation of the relevant models.

To facilitate the efficient production of integrated datasets, we have created, within GCSS, a panel-based activity called Data Integration for Model Evaluation (DIME). DIME was formed to coordinate archival, analysis, and dissemination of integrated datasets for the case studies used to evaluate cloud system models and the parameterizations of clouds in GCMs. The tasks of DIME include the following:

- coordination of data collection, quality checking, product definition, reformatting, archival, and dissemination of a set of case study datasets,
- generation of diagnostic datasets for each case study by combining "local" datasets from field campaigns that produced comprehensive sets of surface-based and aircraft observations with "global" satellite and reanalysis datasets,
- promoting communications between GCSS and GRP,
- limited analysis and comparison of independent measurements to document measurement uncertainties,
- collection of sets of cloud process model outputs for each case study to be combined with the observations in the final products, and
- development of a linked set of Web pages containing documentation, bibliographies, and links to additional related data sources.

Although GCSS at large has been carrying out these tasks at the working group level for some years now, DIME is now centralizing and coordinating some aspects of the activity, thus eliminating unnecessary duplication of effort across working groups, and fostering the generation of more uniform integrated data products.

To draw meaningful conclusions from confrontations of CSRMs and SCMs with data, accurate large-scale advective tendencies are required. Otherwise model results can differ from observations due to errors in forcing, as well as model deficiencies, making model evaluation very difficult. Obtaining accurate large-scale advective tendencies requires intensive observations and special analysis techniques (e.g., Zhang and Lin 1997; Zhang et al. 2001). GCSS has relied on intensive observation periods (IOPs) during large field programs for the required observations and on dedicated analysts to subsequently produce the large-scale advective tendencies. Recently, ARM has undertaken both the collection and analysis of such IOP datasets for more than a dozen multiweek periods at the ARM Southern Great Plains (SGP) site.

We now turn to the role, within GCSS, of the large-scale modeling community. A key goal of GCSS is to promote the development of improved cloud parameterizations for use in climate models. Predictably, however, GCSS has to a large extent been distracted from true parameterization development and evaluation by what we call the "intercomparison trap." Many (although not all) of the GCSS WG activities to date have involved organizing case studies, simulating the cases with multiple CSRMs and other models, and intercomparing the model results and the data. It is a matter of record that such intercomparisons sometimes pay off; an example is shown in Fig. 2, which definitely provides scientifically useful information. Intercomparisons are especially valuable for establishing community benchmarks, and for exposing occasional gross errors in particular models. In the absence of active model development and other substantive scientific work, however, benchmarks would be of little value. For this reason, intercomparisons should be a "background" activity of GCSS, rather than its primary modus operandi. GCSS must focus primarily on specific scientific questions related to cloud parameterization, so that parameterization development occurs. We are therefore consciously steering our work away from the intercomparison mode, and focusing more on evaluation of how cloud processes and feedbacks are represented in climate models.

The GCSS Process Mark 1, as summarized in Fig. 4, portrays the CSRM community as the primary producers of ideas in the form of parameterizations, and the GCM/SCM community as relatively *passive consumers* of these ideas. Experience shows that this is unrealistic, for two reasons. First, the CSRM community does not necessarily know what the GCM/SCM community wants or needs. Second, to the extent that the GCM/SCM community is viewed as playing a relatively passive role, it becomes difficult to involve them in the GCSS WG activities as fully as they need to be in order for the WGs to succeed. In short, we have learned that *parameterization development requires the active participation of large-scale modelers* as well as cloud-system modelers.

The CSRM community has wonderful computational tools, but these tools must be focused on issues of relevance to the GCM community. This has in fact happened in some cases, especially in WGs 1 and 4. We note, however, that these two WGs have enjoyed a relatively high level of participation from the GCM community, and that in fact the GCM-oriented participants have already played a significant role in influencing the research conducted by WGs 1 and 4.

In the GCSS Process Mark 2, the GCM/SCM community poses questions; this is indicated very explicitly in Fig. 5. These questions are closely associated with the conceptual underpinnings of the parameterizations proposed by the GCM/SCM community. Answers are provided by the CSRM community, based on their CSRM simulations and comparisons with observations.

In order for this to work, GCSS must attract sufficiently many representatives of the global modeling community to GCSS WG meetings, and the global modelers must have an active and visible role in the activities. Here a simple practical strategy has been adopted: *Each GCSS WG meeting now features one or two presentations of specific new parameterizations and their performance in SCM tests (and other tests), to be presented by invited representatives of the GCM community.* These presentations are designed to "pose questions" in the sense of Fig. 5.

Within the global modeling community there is a cadre of radiative transfer specialists. Radiative transfer is among the most important climate processes at work in cloud systems. GCSS must address the role of radiative transfer through cloud systems in order to achieve its goal of improving cloud system parameterizations for climate models. Some GCSS WGs have given an appropriate level of attention to radiative processes, while others have focused on cloud dynamical issues with prescribed radiative tendencies. It is essential that radiation processes receive a higher overall level of attention in future GCSS projects. In order for this to happen, it will be necessary to entrain radiative transfer specialists into the GCSS WG activities. The simplest and most effective way to do this is to proactively invite radiative transfer specialists into our WG meetings, give them an opportunity to present their science to the WGs, and engage in dialogues with the aim to identify scientific issues of mutual interest. This is an exercise in scientific matchmaking. The GCSS WG chairs must take it upon themselves to bring the parties together, so that nature can take its course.

SCMs and CSRMs cannot reveal the interactions of parameterized processes with the large-scale dynamics, simply because the large-scale dynamical processes are prescribed. This is an important limitation. The implication is that parameterizations must still be tested in full GCMs. The global modeling community includes the operational NWP centers as well as the climate modeling centers. Operational NWP provides excellent opportunities for comparing model results with data.

GCSS exists to provide and/or stimulate ideas and improvements in parameterization schemes used in both climate and NWP models. Nevertheless, the large-scale modelers continue to provide significant input to the GCSS by identifying the key problem areas for which existing parameterization schemes are inadequate (or nonexistent), and that are considered crucial to the success of GCMs.

NWP has a major role as the principal environment for developing and testing of schemes, and hence can provide feedback and focus to GCSS WGs. NWP can routinely compare the physics of its models with observations in the data assimilation and short-range forecast environment. This allows the separation of problems specific to a physical process from the overall drift of longer climate-type integration.

Most NWP centers now have an in-house SCM, based on their GCM, which serves as a test bed for the development and debugging of model parameterization codes. The SCMs are best utilized in parallel with the ability to extract column data from the forecast or analysis. The resulting datasets allow the time step by time step sampling of the behavior and evolution of all parameters and the dynamical forcing at any location on the globe. In the absence of forcing deduced entirely from observations (a difficult and inevitably limited task), the forcings extracted from the analyses or short-range forecasts allow a much greater range of situations to be studied.

Current short and medium-range forecasts in NWP do not take into account variations in SST. This effectively disables many cloud feedbacks. Seasonal predictions, which are now being made operationally at various NWP centers, do include predicted sea surface temperatures and so cloud feedbacks on seasonal (and shorter) timescales can be examined in the context of seasonal forecasting.

THE VIEW FROM 2002. The GCSS Process Mark 2 was developed during 2000. It is now mid-2002. What has been the impact of the revised process? Here is a brief progress report.

GCSS has acknowledged the importance of the data integration community, including its satellite-based component, in a number of ways. The DOE ARM program provided GCSS WG 4 with unprecedented data integration support for its case-3 model intercomparison project. ARM made most of the necessary IOP measurements, including over 1000 balloon-borne sounding system (BBSS) launches, performed the analyses necessary to produce accurate large-scale advective tendencies of temperature and water vapor, and collected the CSRM and SCM results. GCSS WG 3 has relied on DIME and ISCCP for data integration in support of its mesoscale and large-scale model evaluations. The Kananaskis workshop featured talks by several members of the data integration community.

GCSS has increased the involvement of the GCM/SCM community by including invited GCM parameterization talks at WG meetings and the Kananaskis workshop. The European component of GCSS developed a funded, 3-yr research project called EUROCS (European Project on Cloud Systems in Climate Models) that involves CSRMs, SCMs, and GCMs. EUROCS has two research components, one that coincides with GCSS WG 1's recent studies of the diurnal cycle of marine stratocumulus and continental shallow cumulus, and another that overlaps with GCSS WG 4's recent and current examinations of the diurnal cycle of deep convection over land; in addition, EUROCS is investigating the effects of midtropospheric dry layers on deep convection.

GCSS has increased its emphasis on parameterization issues relative to that on model intercomparisons in two ways. Individual GCSS scientists have used the CSRM "datasets" that are the initial products of a model intercomparison project as a basis or starting point for parameterization testing and development (e.g., vanZanten et al. 1999; Lock et al. 2000; Martin et al. 2000; Grenier and Bretherton 2001; Siebesma et al. 2003; Redelsperger et al. 2000b). Several of the GCSS WGs are also performing their own evaluations of large-scale cloud parameterizations using observations. EUROCS and WG 1 are evaluating the representation of boundary layer clouds in the northeast Pacific Ocean, WG 3 is evaluating frontal and layer clouds in midlatitudes, and WG 5 is evaluating Arctic clouds in regional climate models.

The radiation community is now more involved in GCSS and vice versa. GCSS WGs 1 and 4 have provided 2D and 3D simulated cloud fields for evaluating the impact of various treatments of SGS cloud overlap and inhomogeneity assumptions on solar radiative transfer calculations (e.g., Barker et al. 1999) and for an intercomparison of solar radiative transfer codes (e.g., Barker et al. 2003, manuscript submitted to *J. Climate*). In addition, WG 5 is performing an evaluation of radiative transfer codes applied to Arctic conditions, and several radiative transfer experts gave talks at the Kananaskis workshop. The extensive ARM cloud radar measurements have recently been analyzed to provide new information on cloud overlap (Mace and Benson-Troth 2002). Results like this are bringing parameterization of SGS cloud overlap and cloud inhomogeneity—previously issues that mainly concerned the radiative transfer specialists, and that were buried deep inside the radiative transfer codes—to the attention of the CSRM community.

Based on the recent experience of GCSS, we propose some refinements to the GCSS Process Mark 2. At the heart of these refinements is an increasing recognition that the scales resolved by CSRMs are the most physically appropriate ones for developing and testing cloud parameterizations (e.g., Stevens et al. 1998). An implication is that models (both CSRMs and GCMs/SCMs) should be tested against observed cloud-scale statistics (e.g., Luo et al. 2003). Such statistics can be obtained from, for example, satellites, ground-based cloud and precipitation radars, and mesonets. To compare GCM/SCM results to cloud-scale data, it is necessary to make explicit use of the model's assumptions about SGS inhomogeneity (e.g., Klein and Jakob 1999; Tselioudis et al. 2000; Norris and Weaver 2001). This trend toward dealing more explicitly with cloud-scale processes has been carried to its limit in the recent successful use of CSRMs as "superparameterizations" in GCMs (Grabowski and Smolarkiewicz 1999; Grabowski 2001; Khairoutdinov and Randall, 2001; Randall et al. 2003, manuscript submitted to *Bull. Amer. Meteor. Soc.,* hereafter RKAG). Superparameterizations provide an intrigu-

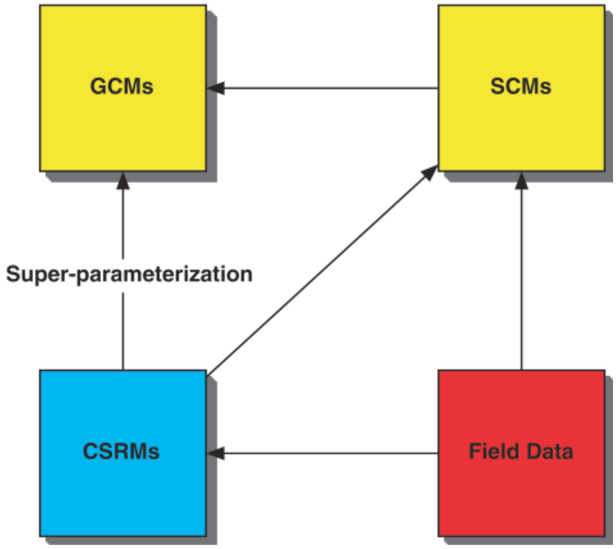


Fig. 6. A modified version of Fig. 1, in which CSRMs interact with GCMs directly through their use as "superparameterizations," as proposed by Grabowski and Smolarkiewicz (1999), Grabowski (2001), Khairoutdinov and Randall (2001), and RKAG.

ing new mode of interaction between the CSRM and GCM/SCM communities (Fig. 6).

As a result of the increasing emphasis on cloud-scale processes, the overlap of the CSRM and GCM/SCM communities has increased, as more CSRMers develop parameterizations and test them in SCMs (e.g., Lock et al. 2000; McCaa et al. 2003, manuscript submitted to *Mon. Wea. Rev.*) and in large-scale models (e.g., Köhler 1999; Martin et al. 2000; McCaa and Bretherton 2003, manuscript submitted to *Mon. Wea. Rev.*; Wu et al. 2002). Superparameterization goes even further by embedding a CSRM in each grid column of a GCM. In addition, the CSRM community is increasingly involved in the evaluation of cloud simulations by GCMs. The walls are coming down.

The 2002 GCSS Workshop in Kananaskis, Alberta, Canada, featured an open discussion on how models and data can be brought together in the framework of GCSS. One of the products of this discussion is shown in Fig. 7, which is modeled after a concept proposed by Jakob (2000). The figure shows how the GCSS Process Mark 2 fits into a larger process of GCM development. One of the key ingredients of this process is the testing of GCMs through numerical weather prediction as well as climate simulation. Figure 7 succinctly summarizes the current process of cloud parameterization development and evaluation, and the role of GCSS in this process.

The Model-Development Machine

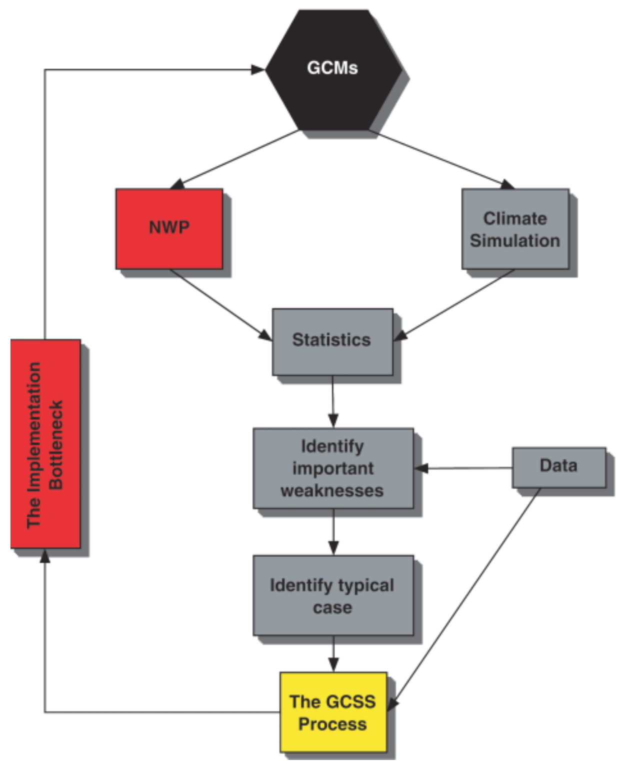


Fig. 7. The "model-development machine," based on a concept by C. Jakob (Jakob 2000), as discussed at the 2002 Pan-GCSS meeting at Kananaskis, Alberta, Canada. The machine is designed to lead to improvements in GCMs (black box at top). A key step, advocated by Jakob (2000) and others, is to test the GCM through NWP for many cases, leading to the development of a database of NWP error statistics. Additional error statistics are compiled through the analysis of climate simulations. Study of these errors leads to the identification of important model weaknesses, and also the design of case studies that focus on the relevant physical processes. The case studies are fed through the GCSS Process Mark 2. Note that data enter at various steps along the way. A remaining problem is the "implementation bottleneck," i.e., the lag between the development of new ideas and their actual implementation in GCMs.

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Figure 2 was provided by Ric Cederwall and Jon Yio of the Lawrence Livermore National Laboratory.

REFERENCES

Barker, H. W., G. L. Stephens, and Q. Fu, 1999: The sensitivity of domain-averaged solar fluxes to assumptions about cloud geometry. *Quart. J. Roy. Meteor. Soc.,* **125,** 2127–2152.

Bechtold, and Coauthors, 2000: A GCSS model intercomparison for a tropical squall line observed during TOGA-COARE: II: Intercomparison of single-column models and a cloud-resolving model. *Quart. J. Roy. Meteor. Soc.,* **126,** 865–888.

Bretherton, C. S., and Coauthors, 1999a: An intercomparison of radiatively-driven entrainment and turbulence in a smoke cloud, as simulated by different numerical models. *Quart. J. Roy. Meteor. Soc.,* **125,** 391–423.

Bretherton, C. S., 1999b: A GCSS boundary layer model intercomparison study of the first ASTEX Lagrangian experiment. *Bound.-Layer Meteor.,* **93,** 341–380.

Browning, K. A., and Coauthors, 1993: The GEWEX Cloud System Study (GCSS). *Bull. Amer. Meteor. Soc.,* **74,** 387–399.

——, and Coauthors, 1994: GEWEX Cloud System Study (GCSS) science plan. IGPO Publ. Series No. 11, World Climate Research Programme, Geneva, Switzerland, 62 pp. and 3 appendixes.

Curry, J. A., and Coauthors, 2000: FIRE Arctic Clouds Experiment. *Bull. Amer. Meteor. Soc.,* **81,** 5–29.

Donner, L. J., C. J. Seman, B. J. Soden, R. S. Hemler, J. C. Warren, J. Strom, and K.-N. Liou, 1997: Large-scale ice clouds in the GFDL SKYHI general circulation model. *J. Geophys. Res.,* **102,** 21 745–21 768.

Grabowski, W. W., 2001: Coupling cloud processes with the large-scale dynamics using the cloud-resolving convection parameterization (CRCP). *J. Atmos. Sci.,* **58,** 978–997.

——, and P. K. Smolarkiewicz, 1999: CRCP: A cloud resolving convection parameterization for modeling the tropical convective atmosphere. *Physica D,* **133,** 171–178.

Grenier, H., and C. S. Bretherton, 2001: A moist PBL parameterization for large-scale models and its application to subtropical cloud-topped marine boundary layers. *Mon. Wea. Rev.,* **129,** 357–377.

Jakob, C., 2000: The representation of cloud cover in atmospheric general circulation models. Ph. D. thesis, Fakultät für Physik der Ludwig-Maximilians-Universität München, Munich, Germany, 194 pp.

Khairoutinov, M. F., and D. A. Randall, 2001: A cloud resolving model as a cloud parameterization in the NCAR Community Climate System Model: Preliminary results. *Geophys. Res. Lett.,* **28,** 3617–3620.

Klein, S. A., and C. Jakob, 1999: Validation and sensitivities of frontal clouds simulated by the ECMWF model. *Mon. Wea. Rev.,* **127,** 2514–2531.

Köhler, M., 1999: Explicit prediction of ice clouds in general circulation models. Ph.D. dissertation, University of California, Los Angeles, 167 pp.

Lock, A. P., 1998: The parameterization of entrainment in cloudy boundary layers. *Quart. J. Roy. Meteor. Soc.,* **124,** 2729–2753.

——, 1999: A parameterization of turbulent mixing in convective cloud-capped boundary layers derived from large-eddy simulations. *Proc. GCSS-WGNE Workshop on Cloud Processes and Cloud Feedbacks in Large-Scale Models,* Reading, United Kingdom, ECMWF, 33–41.

——, and M. K. MacVean, 1999: A parameterization of entrainment driven by surface heating and cloud-top cooling. *Quart. J. Roy. Meteor. Soc.,* **125,** 271–300.

——, A. R. Brown, M. R. Bush, G. M. Martin, and R. N. B. Smith, 2000: A new boundary layer mixing scheme. Part I: Scheme description and single-column model tests. *Mon. Wea. Rev.,* **128,** 3187–3199.

Luo, Y., S. K. Krueger, G. G. Mace, and K.-M. Xu, 2003: Cirrus cloud properties from a cloud-resolving model simulation compared to cloud radar observations. *J. Atmos. Sci.,* **60,** 510–525.

Mace, G. G., and S. Benson-Troth, 2002: Cloud-layer overlap characteristics derived from long-term cloud radar data. *J. Climate,* **15,** 2505–2515.

Martin, G. M., M. R. Bush, A. P Lock, A. R. Brown, and R. N. B. Smith, 2000: A new boundary layer mixing scheme. Part II: Tests in climate and mesoscale models. *Mon. Wea. Rev.,* **128,** 3200–3217.

Norris, J. R., and C. P. Weaver, 2001: Improved techniques for evaluating GCM cloudiness applied to the NCAR CCM3. *J. Climate,* **14,** 2540–2550.

Randall, D. A., K.-M. Xu, R. J. C. Somerville, and S. Iacobellis, 1996: Single-column models and cloud ensemble models as links between observations and climate models. *J. Climate,* **9,** 1683–1697.

——, and Coauthors, 2000: The second GEWEX Cloud Systems Study science and implementation plan. International GEWEX Project Office Series No. 34, 45 pp. [Available from International GEWEX Project Office, 1010 Wayne Ave., Suite 450, Silver Spring, MD 20910.]

Redelsperger, J.-L., and Coauthors, 2000a: A GCSS model intercomparison for a tropical squall line observed during TOGA-COARE. I: Cloud-resolving models. *Quart. J. Roy. Meteor Soc.,* **126,** 823–864.

——, F. Guichard, and S. Mondon, 2000b: A parameterization of mesoscale enhancement of surface fluxes for large-scale models. *J. Climate,* **13,** 402–421.

Rossow, W. B., and R. A. Schiffer, 1999: Advances in understanding clouds from ISCCP. *Bull. Amer. Meteor. Soc.,* **80,** 2261–2287.

Ryan, B. F., and Coauthors, 2000: Simulations of a cold front by cloud-resolving, limited-area and large-scale models and a model evaluation using in situ and satellite observations. *Mon. Wea. Rev.,* **128,** 3218–3235.

Siebesma, A. P., and Coauthors, 2003: A large eddy simulation intercomparison study of shallow cumulus convection. *J. Atmos. Sci.,* in press.

Stevens B., W. R. Cotton, and G. Feingold, 1998: A critique of one- and two-dimensional models of boundary layer clouds with a binned representation of drop microphysics. *Atmos. Res.,* **47–48,** 529–553.

Tselioudis, G., Y. Zhang, and W. B. Rossow, 2000: Cloud and radiation variations with northern midlatitude low and high sea level pressure regimes. *J. Climate,* **13,** 312–327.

Uttal, T., and Coauthors, 2002: Surface heat budget of the Arctic Ocean. *Bull. Amer. Meteor. Soc.,* **83,** 255–275.

vanZanten, M., P. G. Duynkerke, and J. W. M. Cuijpers, 1999: Entrainment parameterizations in convective boundary layers derived from large eddy simulations. *J. Atmos. Sci.,* **56,** 813–828.

World Climate Research Programme, 2000: *Workshop on Cloud Processes and Cloud Feedbacks in Large-Scale Models.* WCRP-110, WMO/TD-993, 175 pp.

Wu, X., M. W. Moncrieff, X.-Z. Liang, and G. J. Zhang, 2002: Evaluation and impact study of convective momentum parameterization using 3D cloud-resolving model and general circulation model. Preprints, *25th Conf. on Hurricanes and Tropical Meteorology,* San Diego, CA, Amer. Meteor. Soc., 198–199.

Xie, S. C., and Coauthors, 2002: Intercomparison and evaluation of cumulus parameterizations under summertime midlatitude continental conditions. *Quart. J. Roy. Meteor. Soc.,* **128,** 1095–1136.

Xu, K.-M., and Coauthors, 2002: An intercomparison of cloud-resolving models with the Atmospheric Radiation Measurement summer 1997 intensive observation period data. *Quart. J. Roy. Meteor. Soc.,* **128,** 593–624.

Zhang, M. H., and J. L. Lin, 1997: Constrained variational analysis of sounding data based on column-integrated budgets of mass, heat, moisture and momentum: Approach and application to ARM measurements. *J. Atmos. Sci.,* **54,** 1503–1524.

——, ——, R. T. Cederwall, J. J. Yio, and S. C. Xie, 2001: Objective analysis of the ARM IOP data: Method and sensitivity. *Mon. Wea. Rev.,* **129,** 295–311.