USE OF SINGLE-COLUMN MODELS AND LARGE-EDDY SIMULATIONS TOGETHER WITH FIELD DATA TO EVALUATE PARAMETRIZATIONS OF ATMOSPHERIC PROCESSES[1]

D. A. Randall
Department of Atmospheric Science
Colorado State University
Fort Collins Colorado 80523 USA

Abstract: Single-column models (SCMs) are the column-physics packages of large-scale models, decoupled from the large-scale model's dynamical framework. Cloud system models (CSMs) are high-resolution cloud-resolving models which are used to simulate many clouds in large spatial domains, over times long compared with the life-time of a single cloud element. Large-eddy simulation models (LESMs) are very-high-resolution models which can represent the turbulent eddies responsible for most transport processes, e.g. in the planetary boundary layer. This chapter deals with the ways in which such models can be combined with field data in order to evaluate physical parameterizations used in large-scale models.

1. INTRODUCTION

How can we test parameterizations that have been developed or are under development for use in general circulation models (GCMs)? The first and most obvious approach is climate simulation itself. Here we "simply" perform a climate simulation and compare the results with observations, as illustrated in the top panel of Fig. 1. An advantage of this approach is that it tests the parameterization as it is intended to be used, i.e. in climate simulation. There are several disadvantages, however. First, the results produced by a climate model are big and complicated, and depend on all aspects of the model, so that it can be very difficult to attribute particular deficiencies of the results to particular aspects of the model's formulation. Second, climate simulations are computationally expensive and time-consuming, so that only a limited number of runs can be made. Finally, the individual weather systems simulated by climate models do not represent particular weather systems in particular places at particular times in the real world, so only statistical comparisons with observations are possible.

Fig. 2 shows how a process-oriented field program can be used to validate and develop GCM

---

[1] This paper summarizes work much of which has been previously published by the American Meteorological Society (Randall et al., 1996) and by the American Geophysical Union (Randall and Cripe, 1999), as well as in the Single-Column Modeling White Paper published by the ARM Program of the U.S. Department of Energy. The latter document was edited and partially written by the present author.

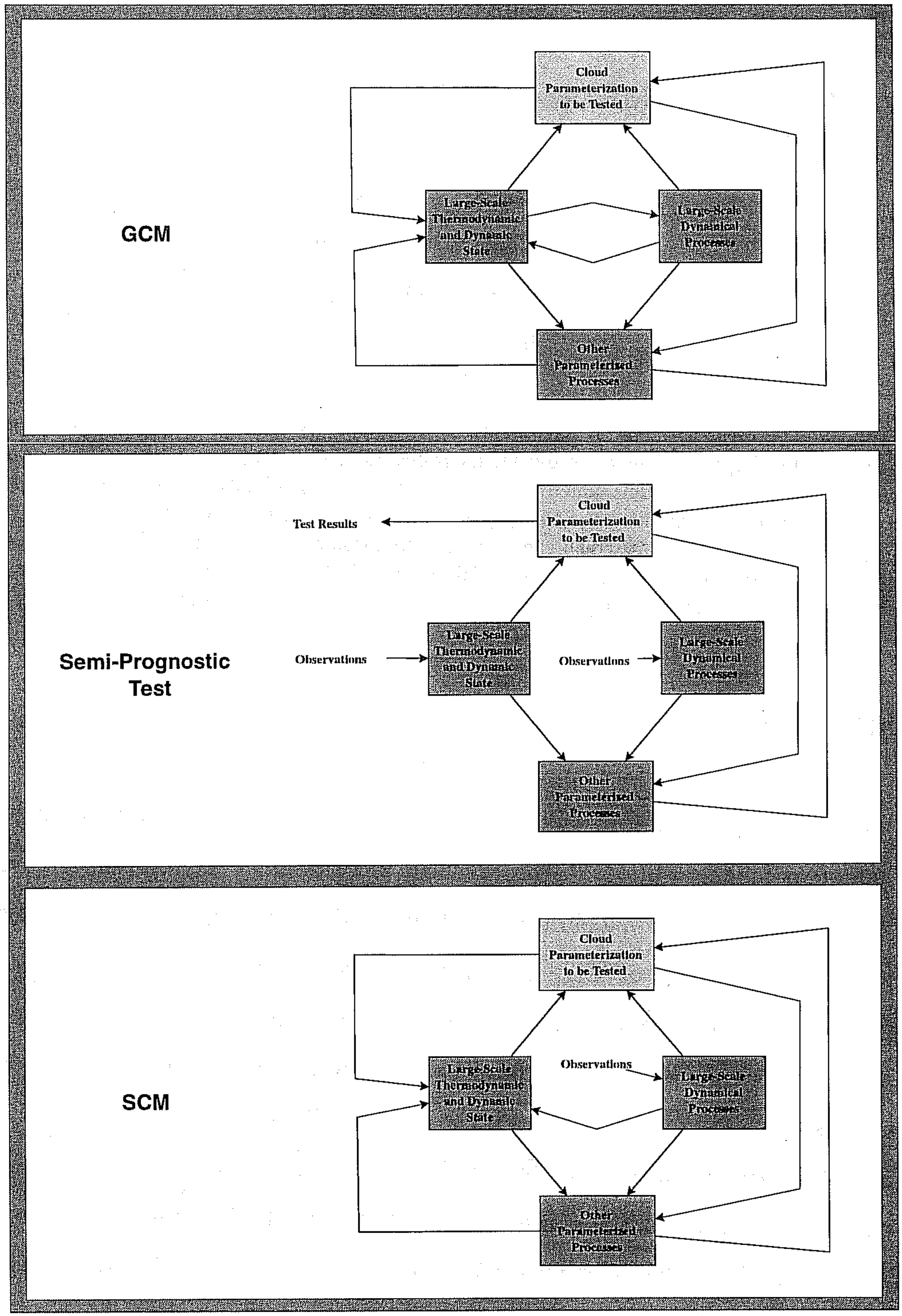


Figure 1. Three ways to test parameterizations: Perform a climate simulation or weather forecast with the parameterization (top panel), perform a semi-prognostic test (center panel), or run the parameterization in a single-column model (bottom panel). See text for details.

parameterizations, and also to validate remote sensing techniques. The GCM is represented by the "black box" at the top center. The GCM can be thought of as a collection of process models, including for example a model to predict cirrus cloud formation. When the GCM is run, it produces climate simulations. Satellite datasets like those produced by ERBE, ISCCP, and EOS can be used to evaluate the realism of the climate simulations.

The satellite datasets can tell us that a climate simulation has failed to reproduce some important aspect of the observed climate, such as the distribution of outgoing longwave radiation, but they cannot tell us *why* the model has failed. The cause of the failure must be determined in order to develop improvements to the model. The cause is a specific weakness or set of weaknesses in one or more of the process models that make up the GCM, e.g. a problem with the cirrus cloud formation parameterization. To find the cause of the problem, it is therefore necessary to make measurements that relate directly to the process models themselves. One implication of this is that the process models must be formulated in such a way that they can be tested against data; this is not always the case, but it *should* always be the case.

A second approach is to use the parameterization in a forecast model, to do numerical weather prediction, and then compare the forecast with observations. This approach can also be represented by the top panel in Fig. 1. An important advantage of this approach is that it allows detailed comparison with data for individual weather events on particular days. It is expensive, however, since numerical weather prediction is an expensive business, although to the extent that the parameterization can be evaluated by using operational forecasts that must be done anyway this problem can be dismissed. As with tests in climate models, the results produced by a numerical weather prediction model are big and complicated, and depend on all aspects of the model, so that again it can be very difficult to attribute particular deficiencies of the forecasts to particular aspects of the model's formulation. A further difficulty is that a very elaborate data-ingest system is needed in order to do numerical weather prediction. Although such systems are in place at operational forecasting centers, they are not ordinarily available at climate modeling centers, and would be prohibitively difficult to set up.

In brutally practical terms, the purpose of any parameterization is to compute certain "tendencies," i.e. partial time rates of change due to the particular process represented by the parameterization. For example, one can say that purpose of a radiation parameterization is to compute radiative heating rates[2]. A parameterization can thus be tested by evaluating its ability to reproduce observed tendencies for a given large-scale situation. This can be done outside the climate model.

There are in fact two approaches that involve testing parameterizations outside the climate model, and predictably both have advantages and disadvantages. The first is the "semi-prognostic test," which was pioneered by Lord (1982), and has also been used by Kao and Ogura (1987) and Grell et al. (1991), among others. In this approach, which is illustrated in the center panel of Fig. 1, a parameterization or suite of parameterizations is exercised in the framework of a single atmospheric column, which can be thought of as a single column taken from a global climate model. A climate model can be considered to be a collection of many such columns, arranged to cover the entire Earth, and interacting with each other through a set of rules known as "large-scale dynamics." In a global climate model, neighboring grid columns provide information that is needed to determine what will happen within the grid column in question; for example, low-level convergence of mass from neighboring columns tends to produce rising motion, and horizontal advection produces tendencies of temperature and moisture. In the semi-prognostic approach, there are no "neighboring grid columns," so all information that is needed and would otherwise be obtained from such columns is provided, instead, from observations. In some cases idealized data may be supplied in place of real observations.

Depending on the specific application, observations may also be used to determine the tendencies due to other processes that would be parameterized within a climate model. This is important because the algorithm for the computation of the tendencies produced by parameterization X on a given time step can require as input those produced by parameterization Y. As an example, if we were testing a cumulus parameterization, as Lord (1982) did, we might use observations to determine the radiative temperature tendencies, and the effects of boundary-layer turbulence on the temperature and humidity of the air near the ground; both of these were in fact needed as input to the convective parameterization that Lord was testing.

To summarize, then, in a semiprognostic test observations are used to prescribe both the state of the atmospheric column and tendencies due to all processes except those associated with the parameterization to be tested. In addition, the current state of the atmosphere is also prescribed from

---

[2] Of course, a radiative transfer specialist would point out that an important additional motivation for the development of a radiation parameterization is to summarize some elements of our understanding of radiative transfer in a compact and relatively simple form. We certainly agree with this.

observations. To the extent that the observations are error-free, any errors in the computed local time rates of change at a given time must be entirely due to problems with the parameterization being tested. The point is that this approach isolates the parameterization being tested from all other components of the model; the test is "clean." This is an important strength of the method. An additional strength is that the semiprognostic test is computationally very inexpensive, compared to running a full large-scale model.

A semiprognostic test can be applied at a sequence of observation times, and we can think of these as being separated by "time steps." Because observations are used to specify the state of the atmosphere at each observation time, errors in the computed tendencies at the previous observation time have no effect; for convenience we summarize this by saying that there is "no feedback" from one time step to the next. This is both an advantage and a disadvantage. It is an advantage because it means that the time-averaged tendencies can be very wrong; a useful test, after all, is one that can be failed in many ways. For example, the parameterization might lead to a systematic erroneous warming tendency of 1 K per day at a certain level. After a sequence of many observation times, this would imply a huge time-accumulated temperature error at that level. The ability to produce such an error, or not, is a strength of the semiprognostic test. In other words, the semiprognostic test is a tough one because it is difficult to reproduce the observed time-mean tendencies.

The lack of feedback from one time step to the next is also a drawback, however, because parameterizations can have deficiencies that arise directly from such feedbacks; problems of this type cannot be detected with semiprognostic tests. A further difficulty with semiprognostic tests is that the data requirements are very challenging. It is necessary to assemble a very complete picture of the large-scale circulation and the various physical processes not being tested, in order to perform semiprognostic tests. This is both expensive and complicated. Data requirements are discussed further below.

The fourth approach for testing climate model parameterizations is somewhat similar to the semiprognostic test; it is called "single-column modeling," and is illustrated in the bottom panel of Fig. 1. As the name suggests, a single-column model (SCM) can be considered to be a grid column of a climate model, again considered in isolation from the rest of the model. As in the semiprognostic test, observations are used to specify what is going on in "neighboring columns," and observations may or may not also be used to specify tendencies due to some parameterized processes, other than those being tested. The key difference between single-column modeling and the semiprognostic test is that in an SCM the results obtained for one observation time are used to predict new values of the prognostic variables, which are then provided as input for the next observation time. Like semiprognostic tests, an SCM run can test a parameterization or a suite of parameterizations without complications from the rest of the global climate model, and it is very inexpensive, but it has demanding data requirements.

A problem with SCMs is that the time-averaged total tendencies have to be about right, i.e. they have to be small, since, for example, various feedbacks will act to prevent an erroneous 1 K per day warming for 30 consecutive days. A second problem is that, although feedbacks that work inside a single column are active in an SCM, others, such as those involving the large-scale circulation, cannot be included. As a result, problems with the parameterization that involve such large-scale feedbacks cannot be detected using an SCM; they are best studied with a full climate model.

There is a second type of model which can be used to develop and test GCM parameterizations, and which can be driven with the same sort of observations as those needed to drive an SCM; this is a cloud system model (CSM). A CSM is a model with sufficient resolution to resolve (at least crudely) the structures of individual clouds (e.g. cumulus clouds), run over a spatial domain large enough to contain many clouds and for a time long enough to include many cloud life cycles. Most CSMs today are two-dimensional, although the increasing power of computers will allow this to change within a few years. The domain of a CSM can be considered to represent a single grid column of a GCM; in this way, a CSM is analogous to an SCM, but a CSM computes clouds and convection explicitly, whereas an SCM must parameterize them. CSMs are in use by many groups today (e.g. Yamazaki, 1975; Krueger, 1988; Nakajima and Matsuno, 1988; Xu et al., 1992; Held et al., 1993; Krueger et al., 1995 a, b; Xu and Randall, 1996 a, b; Sui et al., 1994), in a variety of applications. In this paper we discuss only the use of CSMs for parameterization development and testing.

A CSM computes some things that are very difficult to observe, such as the vertical distribution of liquid water and ice. This simulated information is no substitute for real observations, because CSMs do contain parameterizations, notably microphysics and turbulence parameterizations, which introduce major uncertainties. CSM results are not reality. Nevertheless, CSM results can be judiciously compared with SCM results in order to diagnose problems with the latter.

It is possible to use either a CSM and an SCM to develop or test a parameterization, and it is advantageous to use both. An approach involving both is illustrated in Fig. 3. All information flows from the field data, which are used to drive the SCM and CSM, and also to evaluate the simulations obtained. The results from the CSM can also be compared with those produced by the SCM. Finally, the parameterization tested in the SCM can be transferred directly to a three-dimensional GCM.

Parameterization tests with SCMs and CSMS can be of a "debugging" nature, or they can be physical tests like those indicated in Fig. 3. There are other possible applications, however. For example, an SCM or CSM can be forced with suitable output generated by a climate model, or with idealized forcing designed to mimic a situation of interest, or we can use it to study radiative-convective equilibrium and similar idealized problems (e.g. Held et al., 1993; Sui et al., 1994; Rennó et al., 1994; Randall et al. 1994).

Betts and Miller (1986) pioneered the use of single-column modeling as a tool for testing parameterizations developed for use in large-scale models. A single-column model (SCM) is essentially a single grid column of a global model, considered in isolation from the rest of the model. Observations are used to specify what is going on in "neighboring columns," and observations may or may not also be used to specify tendencies due to some parameterized processes, other than those being tested. An SCM is run prognostically, i.e. the results obtained for one observation time are used to predict new values of the prognostic variables, which are then provided as input for the next observation time. High-resolution cloud system models (CSMs) can be driven with the same input data (e.g. Krueger, 1988). This use of SCMs and CSMs to test parameterizations for large-scale atmospheric models has been adopted as a key strategy of GCSS, the GEWEX Cloud Systems Study (Browning, 1993).

2. DATA REQUIREMENTS

The data requirements for an SCM and a CSM are essentially the same. They are summarized in Table 1. The variables listed in the table are offered only as typical examples; certainly the particulars depend on the formulation of the model and the application at hand.

Among the data needed are time varying vertical profiles of the large-scale vertical motion and the tendencies of temperature and moisture due to horizontal advection. These are, of course, particularly troublesome quantities to observe, and in fact they can only be obtained by very indirect means, which have been developed to overcome problems with missing data, instrument errors, and

Table 1: **Data Requirements for SCMs and CSMs. These lists are intended to be illustrative, rather than comprehensive.**

Initial Conditions
Temperature sounding
Water vapor mixing ratio sounding
Vertical distributions of cloud water and cloud ice
Horizontal wind components (vertical profile needed, but especially PBL values
PBL depth (pressure units) and turbulence kinetic energy (not critical but useful
Ground temperature and wetness
Mass of snow and / or liquid (e.g. dew or rain) stored on vegetation or ground surface
External Parameters
Solar constant
Latitude, longitude, Julian day and GMT
Surface characteristics (elevation, albedo, roughness, vegetation type, etc.
Large-scale divergence
Tendencies of temperature and moisture due to horizontal advection
Pressure gradient force (if winds are predicted)
Momentum advection terms (if winds are predicted
Data for Model Evaluation
All variables for which initial conditions are needed
Cloud amount as a function of height
Precipitation rate
Surface fluxes of sensible heat, moisture, and momentum
The same turbulent fluxes as functions of height
Solar and infrared (broadband) radiation fluxes, from the surface to the top of the atmosphere

incomplete spatial and temporal coverage. Broadly speaking, there are two approaches, and both are used in this paper. First, objective analysis methods can be used to combine measurements from various sources (e.g. rawinsonde data, wind profilers, etc.) in order to obtain synoptic descriptions of the large-scale dynamical and thermodynamic fields. These can then be differentiated (typically by approximate numerical methods) to infer wind divergence, horizontal gradients, etc. A particularly careful example of this approach is described by Ooyama (1987), who applied it to the GATE data.

A second approach is to make use of products obtained through data assimilation at the operational numerical weather prediction centers (e.g. Bengtsson et al. 1982; Trenberth and Olsen 1988). Although such products are readily available and offer high-resolution global coverage with, potentially, high time resolution as well, the physical parameterizations of the forecast model do affect the results, particularly in data-sparse regions. This is a particularly worrisome problem for vertical motion and water vapor. For these reasons, it seems prudent to use pure objective analysis methods whenever possible. Assimilation products nevertheless offer unmatched spatial coverage and comprehensive information about the dynamical fields, and there is no question that they must play a very important role in driving SCMs and CSMs.

One approach to the use of field data for developing and testing cloud formation parameterizations involves the use of single-column models (SCMs). As the name suggests, an SCM represents a grid column of a general circulation model (GCM), considered in isolation from the rest of the model. The basic idea is to measure the external forcing at work on a column of the atmosphere that corresponds to a single GCM grid column, to use models to compute the cloud formation and radiative transfer processes inside the column, and to evaluate the results produced by the models through comparisons with additional observations. The data required for use with an SCM include observed vertical profiles of temperature, water vapor, and condensed water, as well as the large-scale vertical motion and the tendencies of temperature, water vapor, and condensed water due to horizontal advection.

The SCMs are supplemented with more detailed models, which can be called cloud system models (CSMs). A CSM explicitly simulates cloud-scale motions, while parameterizing the smaller-scale turbulent motions. CSMs are designed to simulate the cloud-scale processes that must be parameterized in a GCM or SCM. A CSM domain may be considered to represent a GCM grid column, so that in a sense a CSM can be considered to be a detailed SCM. A CSM typically includes a turbulence parameterization, a bulk ice-phase microphysics parameterization, a cloud microphysics parameterization, and interactive solar and infrared radiation parameterizations. As with an SCM, observed large-scale vertical motion, horizontal advection, and horizontal pressure gradients can be prescribed as forcing functions. The observations of large-scale fields and tendencies required for scientific applications of a CSM are the same as those required by an SCM, and with the exception of the advective tendencies of condensed water these observations can be provided by ARM measurements. CSMs compute some things that are very difficult to observe, such as the vertical distributions of liquid water and ice. This simulated information is no substitute for real observations, because as mentioned above the CSMs do contain parameterizations, notably microphysics and turbulence parameterizations, which introduce major uncertainties. Nevertheless CSM results can be judiciously compared with SCM results in order to diagnose problems with the latter.

It is possible to use either a CSM or an SCM to develop or test a parameterization, and it is advantageous to use both. An approach involving both is illustrated in Fig. 2. All information flows from the field data, which are used to drive the SCM and CSM, and also to evaluate the model results. The results produced by the CSM can also be compared with those produced by the SCM. Finally, the parameterization tested in the SCM can be transferred directly to a three-dimensional GCM.

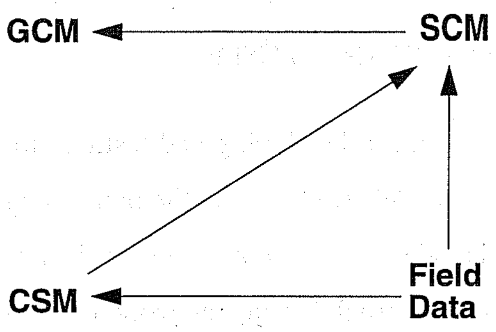


Figure 2. Diagram illustrating how a CSM and an SCM can be combined with field data to develop improved parameterizations for GCMs. The arrows in the figure show the "flow of information." This flow starts with the field data, in the lower right-hand corner of the figure. The observations collected during a field experiment are used with both the CSM 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, for example, 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.

Up to now, almost without exception, evaluations of cloud parameterizations have relied upon comparison of simulated and observed climatological (usually monthly) means of the earth radiation budget or liquid water path. Comparison on shorter time scales has seldom been attempted. Although SCMs are useful testbeds for cloud parameterizations (Randall et al., 1996 a), providing the necessary lateral boundary conditions has proven to be extremely challenging, largely because of sampling and measurement errors in the winds (Zhang and Lin, 1997; Mace and Ackerman, 1996; Randall et al., 1996 a) and because of the lack of cloud measurements along the lateral boundaries (Petch and Dudhia, 1998).

3. SCM METHODS AND METRICS

As discussed above, 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. The importance of such model-data connections can hardly be exaggerated. They are fundamental to the success of ARM, just as they are to the success of any other scientific endeavor.

In one particularly useful approach, multiple SCMs are applied to case studies, so that the ensemble of model results can be *intercompared* among the models and with the field data. As discussed later in this document, ARM's SCM WG has organized one such intercomparison already, and two more are already planned. Intercomparisons of this type are useful in part because they help to bring the modeling community to the table. Participation tends to be strong for several reasons:

- Participants can take advantage of the data preparation carried out by the intercomparison team.
- The intercomparison case represents a standard or benchmark which can be used to perform an evaluation of the performance of a model relative to other models of the same type; and
- there is a perception that failure to participate in such intercomparisons "looks bad."

In a second approach, SCMs can be used to isolate particular physical processes, allowing the effects of other processes to be prescribed for purposes of numerical experimentation. Examples are given by Randall et al. (1996 a).

Finally, SCM studies can suggest ideas which can then be developed and evaluated through theoretical work and/or observational studies.

4. WHAT ARE THE INGREDIENTS OF A SUCCESSFUL SCM STUDY?

The most obvious prerequisite for a successful SCM study is the availability of an SCM. Over the past several years we have seen the creation of SCMs in many if not most of the global modeling centers around the world. NCAR[3] has begun giving an SCM away, complete with a graphical user interface.

In order to perform an SCM study, suitable data are needed. Even after the data have been collected, a strategy is needed for forcing the model with the data. The task of *data integration* is absolutely key to success, and it is a task which is always in danger of getting lost. Data integration consists of bringing together data from disparate instruments, and combining these data into a coherent physical description of what was observed, in a form suitable for use in the evaluation of the relevant models. A climate modeler cannot make 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. The modeler lacks the expertise to analyze such data, and, in any case, such an analysis is a full time job, which if undertaken by the modeler would preclude him or her from doing any modeling.

Perhaps most important of all, a good SCM study needs an idea worth testing. No one should imagine that simply running SCMs with field data somehow solves our scientific problems. The solutions to our problems come in the form of ideas. SCMs cannot in themselves have ideas. The models and the calculations performed with the models cannot free us from the need to generate new ideas about nature by thinking. The development of new parameterizations is typically done with a pencil and paper, during precious and increasingly rare quiet moments of contemplation. Thinking will never be obsolete.

5. WHAT DOES A USEFUL SCM RESULT LOOK LIKE?

An exemplary SCM study is one in which one of the following two possibilities applies:

- A promising new idea (e.g. a cloud formation parameterization) is subjected to tests with field data, using an SCM, and is then adopted for use in an important climate model or a numerical weather prediction (NWP) model.

---

[3] The National Center for Atmospheric Research, which is sponsored by the National Science Foundation.

- Observed but previously unexplained cloud processes are reproduced using an SCM or CSM. Diagnosis of the model results then provides a pathway to understanding the processes in question. This type of study does not necessarily make use of field data, although it may do so.

We should also be endeavoring to understand observed but previously unexplained cloud processes through the use of SCMs and CSMs.

6. SCM-BASED STUDIES AS PART OF A WELL-ROUNDED RESEARCH STRATEGY

SCMs 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 of the SCM strategy. The implication is that, regardless of what may be learned through SCM studies, parameterizations must still be tested in full climate simulations. Tentative "improvements" in parameterizations resulting from SCM research must subsequently be tested in simulations with the parent GCM and the effect of the parameterization change on some important aspect of climate variability or climate change documented. Whenever possible, parameterizations should also be tested through NWP.

7. OBJECTIVE ANALYSIS

Among the data needed for modeling studies that deal with cloud formation processes are time varying vertical profiles of the large-scale vertical motion and the tendencies of temperature and moisture due to horizontal advection. These are, of course, particularly troublesome quantities to observe, and in fact they can only be obtained by very indirect means, which have been developed to overcome problems with missing data, instrument errors, and incomplete spatial and temporal coverage. Broadly speaking, there are two approaches. First, objective analysis methods can be used to combine measurements from various sources (e.g. radiosonde data, wind profilers, etc.) in order to obtain synoptic descriptions of the large-scale dynamical and thermodynamic fields. These can then be differentiated (typically by approximate numerical methods) to infer such quantities as wind divergence and horizontal temperature and moisture gradients.

Estimates of dynamical and thermodynamical fields based on objective analysis (without a first guess provided by a model) are independent of physical parameterizations, which is a highly desirable feature. Some preliminary studies suggest, however, that the errors associated with objective analysis are sometimes too large to meet the stringent SCM measurement requirements. The errors are likely to be particularly large in data-sparse regions such as the Tropical West Pacific (TWP) and North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) or for variables either poorly sampled or subject to large measurement errors (i.e., water vapor, microphysical parameters, and vertical motion).

Besides pure objective analysis, it also possible to use analyses generated through data assimilation. In some cases, this may be the only option. Caution is needed to ensure that the physical parameterizations of the model used in the assimilation process do not adversely affect the relevant aspects of the assimilation products.

8. SPECIFICATION OF THE LARGE-SCALE FORCING

In the research strategy outlined above, an SCM and a CSM are forced with observed, objectively analyzed fields. As discussed by Randall and Cripe (1999), are many possible ways to do this. Consider an arbitrary scalar variable, q, satisfying a conservation equation in "flux-form:"

$$\frac{\partial q}{\partial t} = -\left[\nabla \bullet (Vq) + \frac{\partial}{\partial p}(\omega q)\right] + P \quad . \qquad (1)$$

Here P represents the "physics" that affects q. The continuity equation corresponding to (1) is

$$\nabla \bullet V + \frac{\partial \omega}{\partial p} = 0 \quad . \qquad (2)$$

By using (2) in (1), we can rewrite our conservation equation in "advective form:"

$$\frac{\partial q}{\partial t} = -\left(V \bullet \nabla q + \omega\frac{\partial q}{\partial p}\right) + P \quad . \qquad (3)$$

Neither an SCM nor a CSM can predict the horizontally domain-averaged divergence, $\nabla \bullet V$, so if (2) is to be used to obtain the vertical velocity, then $\nabla \bullet V$ must be prescribed from observations.

Similarly, neither an SCM nor a CSM can determine the horizontally domain-averaged horizontal advective tendency, $-\nabla \bullet (Vq)$ or $-V \bullet \nabla q$, so it is necessary to prescribe some information about the horizontal advection of q.

Some investigators have experimented with an artificial "relaxation" term added to the right-hand side of (3), i.e.

$$\frac{\partial q}{\partial t} = -\left(V \bullet \nabla q + \omega \frac{\partial q}{\partial p}\right) + P + \frac{(q_{obs} - q)}{\tau} \quad , \tag{4}$$

where q_{obs} is the observed value of q, and τ is a specified "relaxation time scale," which is specified to be on the order of a day to perhaps half a day. The effect of the relaxation term is to prevent the predicted value of q from drifting very far away from the observed value, q_{obs}. A problem with the relaxation term is that it does not represent any real physical process. Its "observed" value is, therefore, zero.

8.1 Revealed forcing

One approach to specifying the large-scale advective forcing is simply to compute $-\left(V \bullet \nabla q + \omega \frac{\partial q}{\partial p}\right)$ directly from the analyzed observations (e.g. Redelsperger et al., 1998; Bechtold et al., 1998), and then prescribe these values in the SCM:

$$\frac{\partial q}{\partial t} = -\left(V \bullet \nabla q + \omega \frac{\partial q}{\partial p}\right)_{\text{obs}} + P \quad . \tag{5}$$

We refer to this as "revealed forcing." With this simple approach, errors in the predicted vertical distribution of q have no effect on the advective tendency of q. Revealed forcing is very simple, but it fails to take into account how simulated changes in the sounding would affect the tendencies due to vertical advection.

8.2 Horizontal advective forcing

A simple modification of revealed forcing, which we call horizontal advective forcing, consists of prescribing $-V \bullet \nabla q$ and ω from the observations, and using the *predicted* profile of q, together with the prescribed ω, to evaluate $-\omega\frac{\partial q}{\partial p}$ as the model runs:

$$\frac{\partial q}{\partial t} = -(V \bullet \nabla q)_{\text{obs}} - \omega_{\text{obs}}\frac{\partial q}{\partial p} + P \quad . \tag{6}$$

Horizontal advective forcing allows the tendency of q due to vertical advection to depend on the predicted profile of q, as it does in nature and as it would in a full three-dimensional model; this dependency is missing with revealed forcing.

8.3 Relaxation forcing

Consider (1), i.e. the flux form of the prognostic equation for q. Using Gauss's Theorem, we can rewrite the horizontal flux divergence term of (1) as

$$\nabla \bullet (Vq) = \frac{1}{A}\oint(V_n q)dl \ , \tag{7}$$

where the line integral is taken around the boundary of the region, A is the area of the region, and V_n is the outward normal component of V. We can divide this line integral into two parts: the integral over the portion of the boundary where the wind is blowing into the region, and the integral over the portion of the boundary where the wind is blowing out of the region. Then (7) becomes

$$\nabla \bullet (Vq) = \frac{1}{A}[-(V_{\text{in}}\Delta l_{\text{in}} q_{\text{in}}) + (V_{\text{out}}\Delta l_{\text{out}} q_{\text{out}})] \quad , \tag{8}$$

where the first term represents the inflow (hence the minus sign), and the second represents the outflow. Note that we have defined V_{in} and V_{out} in such a way that

$$V_{\text{in}} \geq 0 \text{ and } V_{\text{out}} \geq 0 \tag{9}$$

are guaranteed.

Next, we modify (8) by adding and subtracting terms involving q, where q is interpreted as the area-averaged value of q for the cell:

$$\begin{aligned} \nabla \bullet (Vq) = {} & \frac{1}{A}\{-[V_{\text{in}}\Delta l_{\text{in}}(q_{\text{in}} - q)] + [V_{\text{out}}\Delta l_{\text{out}}(q_{\text{out}} - q)]\} \\ & + \frac{q}{A}[-(V_{\text{in}}\Delta l_{\text{in}}) + (V_{\text{out}}\Delta l_{\text{out}})] \ . \end{aligned} \tag{10}$$

We recognize the quantity on the second line of the right-hand side of (10) as $q\nabla \bullet V$, so that (10) is equivalent to

$$\nabla \bullet (Vq) = \frac{1}{A}\{-[V_{\text{in}}\Delta l_{\text{in}}(q_{\text{in}} - q)] + [V_{\text{out}}\Delta l_{\text{out}}(q_{\text{out}} - q)]\} + q\nabla \bullet V \quad , \tag{11}$$

or

$$V \bullet \nabla q = \frac{1}{A}\{-[V_{\text{in}}\Delta l_{\text{in}}(q_{\text{in}} - q)] + [V_{\text{out}}\Delta l_{\text{out}}(q_{\text{out}} - q)]\} \quad . \tag{12}$$

Eq. (12) is essentially a finite-difference scheme, which can be used to diagnose $V \bullet \nabla q$; each of the quantities on the right-hand side of (12) can be inferred from a sufficiently detailed set of data.

Now suppose that

$$q - q_{\text{out}} = f(q_{\text{in}} - q) \ , \tag{13}$$

which is equivalent to

$$q = \frac{q_{\text{out}} + f q_{\text{in}}}{1+f} \ . \tag{14}$$

Eq. (13) is nothing more than the definition of f. The data can be used to compute f for a given observation time, and the data together with model results can be used to compute f for a given simulation time. For

$$f \geq 0 \ , \tag{15}$$

q is bounded by q_{out} and q_{in}, or in other words q changes monotonically across the grid cell. For $f = 1$, (13) reduces to $q - q_{\text{out}} = q_{\text{in}} - q$, which simply means that q lies half-way between q_{in} and q_{out}; this should be approximately true in most cases, so we expect that f will often be close to one. When $f < 0$, the grid cell contains a local maximum or minimum of q.

With the use of (13), we can re-write (12) as

$$-\boldsymbol{V} \bullet \nabla q = \frac{q_{\text{in}} - q}{\tau_{\text{adv}}} \ , \tag{16}$$

where we define

$$\frac{1}{\tau_{\text{adv}}} \equiv \frac{(V_{\text{in}} \Delta l_{\text{in}}) + f(V_{\text{out}} \Delta l_{\text{out}})}{A} \ . \tag{17}$$

So long as (15) is satisfied, we are guaranteed that

$$\tau_{\text{adv}} \geq 0 \ . \tag{18}$$

This essentially follows from (9). Note that (18) can be satisfied even for $f < 0$. Eqs. (16) and (17) are analogous to an “upstream” advection scheme for a numerical model.

Finally, we substitute (16) in (10), to obtain

$$\frac{\partial q}{\partial t} = \frac{q_{\text{in}} - q}{\tau_{\text{adv}}} - \omega\frac{\partial q}{\partial p} + P \quad . \tag{19}$$

The meaning of (16) and (19) is that horizontal advection acts like a relaxation of q towards q_{in}, with relaxation time scale τ_{adv}. We can use (19) to predict q, utilizing the predicted value of q on the right-hand side. This means that the horizontal advection term of (19) is determined partly through the observed values of q_{in} and τ_{adv}, and partly through the simulated value of q. Obviously the relaxation term of (19) drives q towards q_{in}, so that if τ_{adv} is short enough (i.e. if the advecting wind is strong enough) then q cannot be very different from q_{in}.

The observed value of $-(V \bullet \nabla q)_{\text{obs}}$ provides information about the gradient of q, but not about the actual value of q. The SCM is started from the observed value of q, but after some time errors in the prescribed horizontal advective tendency and/or errors in the SCM physics can drive the simulated sounding away from the evolving observed sounding; the model "gets lost." This can happen due to errors in the observed advective tendencies, even if the SCM physics is perfect. Because the inserted data do not contain information about the actual value of q, the model has no way to find its way back home, i.e. to return to a sounding that is in agreement with the observations.

Compare (19) with (4). The relaxation term of (4) is added artificially, *in addition* to the horizontal advection term. The relaxation time scale in (4) is arbitrarily specified. The relaxation in (4) is towards q_{obs}, the observed value of q in the region. The relaxation term of (4) cannot be compared with observations because it does not represent a real physical process; one could say, however, that the observed value of the relaxation term of (4) is zero.

In contrast, the relaxation term of (19) *is identically the horizontal advection term*. The relaxation time scale τ_{adv} can be computed directly from the wind data and does not have to be specified arbitrarily. The relaxation in (19) is towards q_{in}, the observed property of the air entering the region. The relaxation term of (19) can be compared with the objectively analyzed value of $-V \bullet \nabla q$, which varies with time and height.

Before we can actually use (19), it is necessary to diagnose q_{in} and τ_{adv} from the objective analysis scheme. We make the following simplifying assumptions: $f = 1$; $V_{\text{in}} = V_{\text{out}} \equiv V$, where V is the average wind speed in the region; and $\Delta l_{\text{in}}/A = \Delta l_{\text{out}}/A = 1/d$, where d is a length scale that is closely related to the distance across the region (depending on wind direction). Then (17) reduces to

$$\frac{1}{\tau_{\text{adv}}} = \frac{2V}{d} , \qquad (20)$$

and (16) yields

$$q_{\text{in}} = q - \tau_{\text{adv}} V \bullet \nabla q \ . \qquad (21)$$

All of the quantities on the right-hand sides of (20) and (21) are observable. With this approach, we can diagnose values of τ_{adv} and q_{in} directly from the observations. These values can then be used with the SCM and/or the CSM.

9. DATA

The data to be discussed here came from three sources:

- the Southern Great Plains site of the Atmospheric Radiation Measurements Project (ARM);
- the Global Atmospheric Research Program's (GARP) Atlantic Tropical Experiment (GATE); and
- the Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA-COARE).

A brief description of these datasets follows.

9.1 ARM

ARM's Southern Great Plains (SGP) site in north-central Oklahoma and south-central Kansas (Stokes and Schwartz, 1994) furnished data for six of the SCM simulations discussed in the present study. A variety of instruments collect data at the ARM site on an on-going basis. In addition, Intensive Observation Periods (IOPs) are conducted quasi-periodically throughout the year, most lasting approximately three weeks. During these IOPs data are collected with increased frequency, and in particular radiosondes are launched every three hours from four positions around the perimeter of the site, as well as from its center. The four launch positions on the site's periphery coincide with the locations of National Oceanic and Atmospheric Administration wind profilers. Precipitation data were provided by the Oklahoma mesonet and Kansas State University mesonet systems in addition to that reported from Surface Meteorological Observing System (SMOS) automated sensors at various locations around the SGP CART site.

The data obtained from the radiosondes and wind profilers were subjected to objective analysis (Leach et al., 1996, 1997). For the July 1995 IOP only, we used a modified version of the objectively analyzed data, which has been subjected to variational constraints, as discussed by Zhang and Lin (1997).

Because the ARM data comes from a land site, and because our study focuses on cloud processes in the atmosphere, we prescribed the surface fluxes from the observations.

9.2 GATE

The GATE data used here are based on Ooyama's (1987) scale-controlled objective analysis of the data obtained by a network of ship observations and radiosonde launches in the eastern Atlantic Inter-Tropical Convergence Zone during Phase III of GATE, as described by Reed et al. (1977) and Thompson et al. (1979). Surface precipitation rates were provided by 3-hourly radar observations (Hudlow and Patterson, 1979). Estimates of the surface fluxes were obtained from E. Recker of the University of Washington (personal communication).

9.3 TOGA-COARE

We used the TOGA-COARE analyses of Lin and Johnson (1996 a, b). All wind and thermodynamic data from the soundings were objectively analyzed using multiquadratic interpolation (Nuss and Titley, 1994) onto a 1-by-1 degree grid over the TOGA-COARE Large Scale Array. The 25 data points that fell within the perimeter of the Intensive Flux Array (IFA) were averaged together. These analyses were carried out for all 480 of the 6-hourly observations collected during TOGA-COARE. Rainfall rates were computed by subtracting averaged surface evaporation rates from the net surface moisture source as inferred by vertical integration of the analyzed apparent moisture sink (Yanai et al., 1973). Sea surface temperatures and surface fluxes represent the averages of measurements collected at several buoys in the IFA.

9.4 Discussion

The GATE and TOGA COARE data were collected in warm, convectively active regions of the tropical oceans. In contrast, the ARM data is from a midlatitude land site. The ARM data includes warm-season, convectively active IOPs, and also cool-season IOPs. The data used in this study allow us to explore the strengths and weaknesses of the various SCM forcing strategies for both tropical and seasonally varying extratropical conditions. In GATE and TOGA COARE, the temporal fluctuations of temperature (especially) and moisture are quite small. In addition, the horizontal advection term of (3) is quite small, especially for the case of temperature. At the midlatitude ARM site, the temporal fluctuations of temperature and moisture can be much stronger than those observed during GATE and TOGA COARE, and in addition the horizontal advective tendencies of temperature and moisture can be much more dramatic.

10. MODEL DESCRIPTION

The SCM used here is a single-column version of the Colorado State University GCM. The SCM and the GCM are actually the same computer code; options can be selected at compilation time to control whether the model runs in three-dimensional (GCM) or one-dimensional (SCM) mode. The model uses a stretched vertical coordinate in which the top of the planetary boundary layer (PBL) is a coordinate surface (Suarez et al., 1983). The PBL is then identically the lowest layer of the model. The depth and turbulence kinetic energy of the PBL are prognostic (i.e. time-stepped) variables of the model.

The cumulus parameterization is based on the ideas of Arakawa and Schubert (1974), but with the prognostic convective closure described by Randall and Pan (1993) and Pan and Randall (1998), and with multiple cloud-base levels as reported by Ding and Randall (1998). Except as noted, for all runs described in this paper, the parameters α and τ_D, used in the convection parameterization and discussed in detail by Pan and Randall (1998), were set to 10^8 m^4 kg^{-1} and 10^3 s, respectively. The model results do depend significantly on the value of α used. The baseline choice, $\alpha = 10^8$ m^4 kg^{-1} is not necessarily optimal, and in fact for the example presented in detail in the next section $\alpha = 10^9$ m^4 kg^{-1} gives noticeably more realistic simulations. This paper is not about cumulus parameterization, and the physical interpretation of α will not be discussed here; such a discussion is given by Pan and Randall (1998). Nevertheless we will discuss the results of experiments in which the value of α is varied. The purpose of these experiments, in the context of the present paper, is to investigate how the results depend on the method by which the SCM is forced. This allows us to illustrate some important differences among the forcing methods.

The stratiform cloud parameterization used in the model was developed by Fowler et al. (1996) and Fowler and Randall (1996 a, b). The radiation parameterization is that of Harshvardhan et al. (1987). The model also includes the land-surface parameterization developed by Sellers et al. (1996 a, b) and tested by Randall et al. (1996 b), but as already mentioned the land-surface model is not used in the ARM SCM runs described here; instead, we prescribed the surface fluxes of sensible and latent heat according to observations.

11. RESULTS

In this discussion, we use the abbreviations RF for Revealed Forcing, HF for Horizontal Advective Forcing, and XF for Relaxation Forcing. Randall and Cripe (1999) show that in a simulation of the July 1995 ARM SCM IOP, the RH and HF simulations are only modestly successful in reproducing the observed fluctuations of temperature and water vapor on a level-by-level basis. The observed PW variations are more successfully simulated in these runs, as are the observed surface precipitation variations. Although the temperature and water vapor soundings obtained with relaxation forcing are much more realistic than those obtained with revealed forcing or horizontal advective forcing, the simulated precipitation rate in the XF run is actually much less realistic than in the RF and HF runs. Randall and Cripe (1999) find that, overall, there are no unambiguous differences between revealed forcing and horizontal advective forcing. The two methods appear to be generally comparable.

Revealed forcing may, therefore, be preferred for its simplicity.

Fig. 3 shows the root-mean-square errors for the vertically integrated temperature, the total column

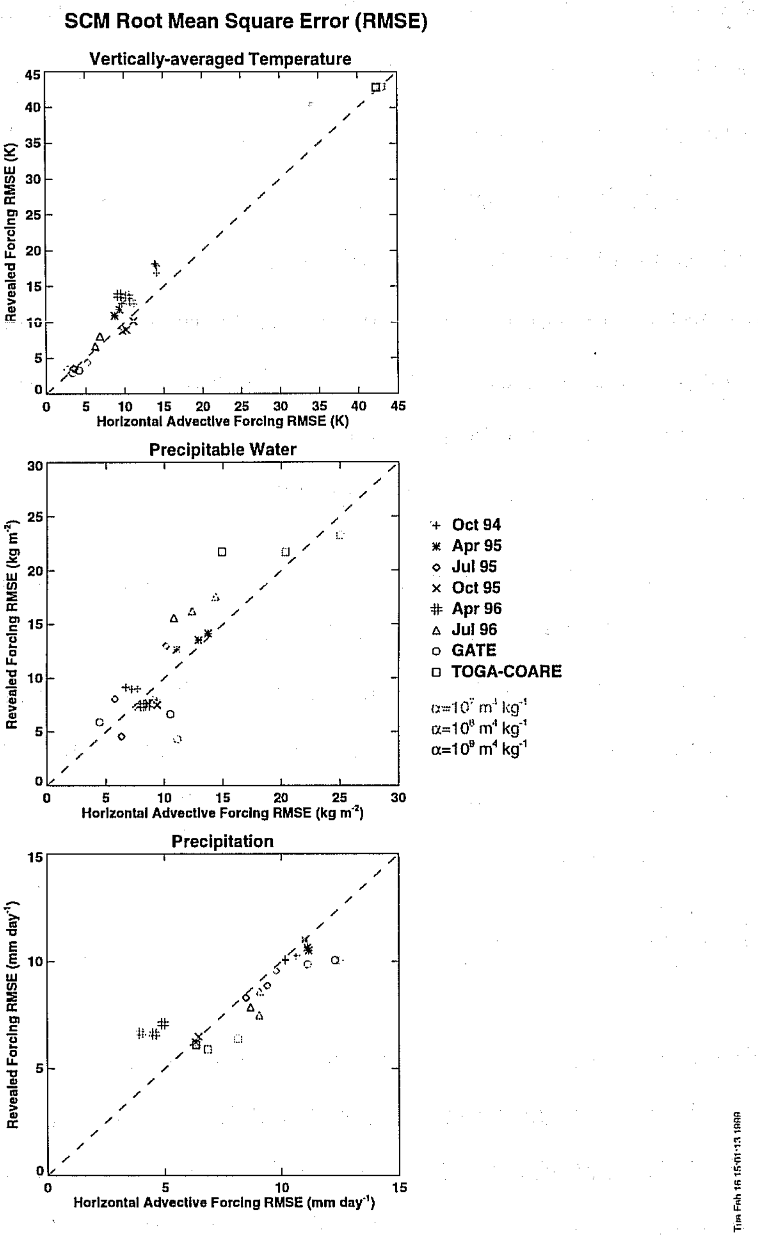


Figure 3. Root-mean-square errors for the vertically integrated temperature (top panel), the total column water vapor (center panel) and the precipitation rate (bottom panel), for the various cases considered, and for three different values of α. Here the "error" in each case is the difference between the simulation and the observation, and "mean" refers to the time average over the entire simulation. The vertical axes show the errors for revealed forcing, and the horizontal axes show the errors for horizontal advective forcing. Along the diagonal line, the two root-mean-square errors are equal.

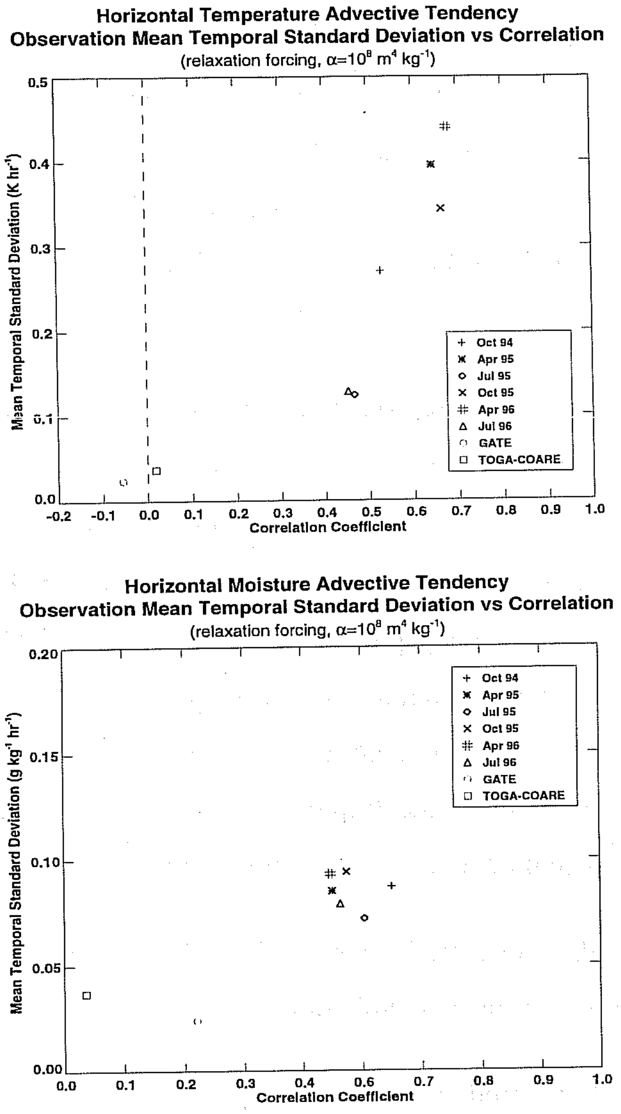
water vapor, and the precipitation rate, for each of the various cases considered, and for three different values of α. Here the "error" in each case is the difference between the simulation and the observation, and "mean" refers to the time average over the entire simulation. The vertical axes show the errors for revealed forcing, and the horizontal axes show the errors for horizontal advective forcing. Along the diagonal line, the two root-mean-square errors are equal. For the vertically integrated temperature and total column water vapor, revealed forcing gives larger errors overall. For the precipitation rate, horizontal advective forcing gives larger errors overall, with the exception of one of the ARM IOPs.

As shown in Fig. 4, the XF runs can reproduce the observed horizontal advective tendencies most successfully when those tendencies are large. Here results are shown for $\alpha=10^8$ m^4 kg^{-1}only. The observed advective tendency of temperature is very poorly simulated for GATE and TOGA COARE, simply because the observed tendencies are tiny in those cases. A small error in the simulation can easily mask the small observed tendency, preventing it from being accurately diagnosed. In addition, the small observed values probably contain large fractional uncertainties. An implication of this result is that relaxation forcing is not suitable for use in the tropics because the observed horizontal advective tendencies are so small in the tropics that they cannot be accurately diagnosed, thus limiting our ability to compare model results with observations.

Relaxation forcing gives the most realistic soundings. Nevertheless, in many cases, relaxation forcing gives the *least* realistic surface precipitation rate.

In general the model tends to produce more humid (in the sense of total column water vapor) soundings when α is large, and drier soundings when α is small. The top panel of Fig. 5 shows graphically that, in particular, this is true for the XF runs. When convection is active the simulated atmosphere becomes drier as α decreases. For $\alpha=10^7$ m^4 kg^{-1}, the simulated atmosphere is considerably drier than observed, while for $\alpha=10^9$ m^4 kg^{-1} it is slightly more humid than observed. In short, for small α the model "runs dry," while for large α it "runs wet." The physical explanation for this is discussed by Pan and Randall (1998); for purposes of the present paper, this explanation is irrelevant. Here we simply take advantage of the fact that we can make the model run wet or run dry by altering the value of α.

As already discussed, the precipitation rate tends to be very unrealistic in the XF runs, despite the



Fri Feb 12 09:41:28 1999

Figure 4. For the various simulations with relaxation forcing, the horizontal axis represents the correlation of the diagnosed horizontal advective tendency with the corresponding observations, and the vertical axis represents the standard deviation of the observed horizontal advective tendency. Here we show only results obtained with $\alpha = 10^8 \text{ m}^4 \text{ kg}^{-1}$. When the observed standard deviation is high, the correlation is high.

fact that the XF-simulated soundings are generally more realistic in the XF runs. Fig. 5 shows that for the XF runs with small α the precipitation rate is higher, while with larger α it is lower. This is particularly true for those IOPs in which convection was active.

The interpretation of these results is very simple: In a model that tends to run drier than observed (i.e. with small α), relaxation forcing fights back against this drying by trying to moisten the sounding,

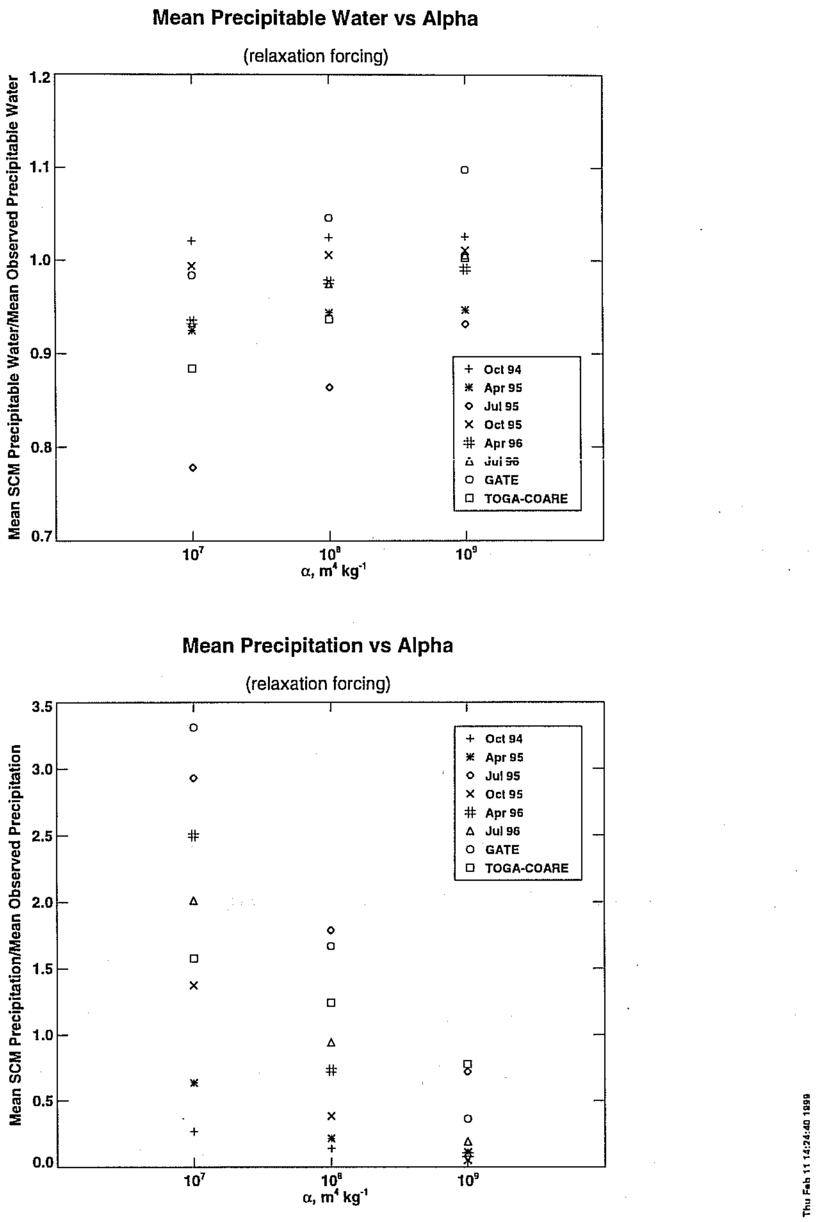


Figure 5. Plots of the mean total column water vapor (upper panel) and mean precipitation rate (lower panel) as functions of α, for the various cases, with relaxation forcing.

and the parameterizations of the model, in turn, fight back against the relaxation by drying the sounding through precipitation. As a result, relaxation forcing leads to excessive precipitation in a model that tends to run dry. In a model that tends to run wet, relaxation forcing tends to dry out the sounding, and so inhibits precipitation.

These results indicate that "error is conserved." With RF and HF forcing, the precipitation rates are relatively realistic but the soundings deviate substantially from the observations, and this tells us that something is wrong with the model. With XF forcing, the soundings are guaranteed to be relatively realistic, but the precipitation rates deviate greatly from the observations, telling us again that there are problems with the model. This indicates that relaxation does not hide the problems of a model; it only changes the way in which those problems manifest themselves.

12. NEW TECHNICAL METHODS FOR FUTURE SCM RESEARCH

Clouds advecting into the SCM domain pose very significant problems, especially for cirrus clouds. The errors due to neglecting condensate advection could be at least as important as the errors present in the analyzed advective forcings of potential temperature and water vapor. We must find a way to measure the advective tendencies of condensed water variables. This might be achieved through use of multiple doppler cloud radars. It will certainly be an issue in any and all future programs focusing on large-scale cloudiness.

At present SCM work is going on at many centers around the world, but there is no standardized format for the forcing data used to drive an SCM. A standardized format could be very useful, and should be pursued through appropriate channels.

13. FROM SCM TECHNOLOGY TO SCM SCIENCE

We have focused, up to now, on what might be called the "technology" of SCM research. This is apparent in a brief summary of the steps we have followed to reach our current status:

- An observing system has been designed, implemented and improved.
- Data have been collected.
- Analysis methods have been designed, tested and improved.
- Modelers have been exposed to the data.
- Methods to force the models with data have been devised and tested and improved.
- Meanwhile, all along the way, new parameterizations have been developed (and are being

developed), through the efforts of ARM scientists and others.

We are thus poised to enter a new phase of SCM research, in which the SCM test, making use of field data, becomes a standard and accepted way of evaluating new parameterizations, at virtually all large-scale modeling centers (and centres). A lot of new SCM work is now coming out (e. g. Ghan et al., 1999 a, b).

14. SENSITIVE DEPENDENCE ON INITIAL CONDITIONS, AND STATISTICAL ANALYSIS OF SCM RESULTS

Several SCM and CSM research teams have found that their model results can be sensitive to the details of the initial conditions used (e.g. Hack and Pedretti, 1999). This is not surprising, because such sensitive dependence on initial conditions is a well-known property of nonlinear systems (Lorenz, 1963), and our models are certainly highly nonlinear. An implication of this finding is that we should be examining ensembles of simulations for a given case, rather than single simulations.

There is some evidence that CSMs are less sensitive to initial conditions that SCMs. This is disturbing, because in principle SCMs are supposed to give the same solutions as CSMs, for a given case. The exaggerated sensitivity of SCMs, if it is real, may arise from the “if tests” which can be found in most parameterizations. This suggests that the elimination of such tests and a reduction of the sensitivity of SCMs to their initial conditions should be a goal of future research on parameterization development.

With or without ensembles of simulations, strategies must be pursued for statistical analysis of SCM and CSM results. Such analyses might take the form of compositing according to the phase of the diurnal cycle phase, the stage of cloud system development, the dynamical sector of a cloud system, or correlations with various large-scale environmental parameters. Such compositing can filter out uninteresting random errors and expose physically important systematic errors.

In order to follow this approach, we need a sufficiently large sample. If a typical IOP is 3 weeks in length, 6-7 IOPs in a given season might be required for a statistically significant sample. This is one of argument in favor of maintaining an extended presence in the field.

15. SUMMARY AND CONCLUSIONS

SCM research is one important strategy for tying field measurements to GCMs. Other strategies include NWP and global climate modeling.

Elaborate methods have been developed for the analysis of field data, in order to facilitate its use with our SCMs and CSMs.

Relaxation forcing can very clearly reveal certain types of model deficiencies which might be overlooked in studies based on revealed and/or horizontal advective forcing.

Our results suggest that revealed forcing gives larger errors in the soundings, while horizontal advective forcing gives larger errors in the precipitation rate. The differences are fairly small and may not be significant. Further study is needed on this point.

Our results clearly demonstrate that relaxation forcing is not well suited for use with tropical datasets, because the observed tendencies of temperature and water vapor are so small in the tropics that it is virtually impossible to diagnose them accurately in terms of model output, using the methods discussed here.

One of the most important current difficulties is analyzing the observed advective tendencies of condensed water variables.

16. ACKNOWLEDGEMENTS

Much of the work reported here has been supported by the U. S. Department of Energy's ARM Program under Grant No. DE-FG02-92ER61363 to Colorado State University. TOGA-COARE data were kindly provided by Richard Johnson and Paul Ciesielski of Colorado State University. Doug Cripe of Colorado State University performed the SCM runs with the CSU SCM, and assisted in the analysis of the results from that model. Ric Cederwall, Jon Yio, and Marty Leach of the Lawrence Livermore National Laboratory were instrumental in providing the ARM data used in this study.

I am grateful to ECMWF for supporting my participation in this Seminar.

17. REFERENCES

Arakawa, A., and W. H. Schubert, 1974: The interaction of a cumulus cloud ensemble with the large-scale environment, Part I. *J. Atmos. Sci.*, **31**, 674-701.

Bechtold, P., J. L. Redelsperger, I Beau, M. Blackburn, S. Brinkop, J. Y. Grandpeix, A. Grant, D. Gregory, F. Guichard, C. Hoff, and E. Ioannidou, 1998: A GCSS model intercomparison for a tropical squall line observed during TOGA-COARE. Part II: Intercomparison of SCMs with CRM. Submitted to *Quart. J. Roy. Meteor. Soc.*

Bengtsson, L., M. Kanamitsu, P. Kallberg, and S. Uppala, 1982: FGGE 4-dimensional data assimilation at ECMWF. *Bull. Amer. Meteor. Soc.*, **63**, 29-43.

Betts, A. K., and M. J. Miller, 1986: A new convective adjustment scheme. Part II: Single column tests using GATE wave, BOMEX, ATEX, and arctic air-mass data sets. *Quart. J. R. Met. Soc.*, **112**, 693-709.

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

Ding, P., and D. A. Randall, 1998: A cumulus parameterization with multiple cloud-base levels. *J. Geophys. Res.*, **103**, 11341-11354.

Fowler, L. D., D. A. Randall, and S. A. Rutledge, 1996: Liquid and Ice Cloud Microphysics in the CSU General Circulation Model. Part 1: Model Description and Simulated Microphysical Processes. *J. Climate*, **9**, 489-529.

Fowler, L. D., and D. A. Randall, 1996 a: Liquid and Ice Cloud Microphysics in the CSU General Circulation Model. Part 2: Simulation of the Earth's Radiation Budget. *J. Climate*, **9**, 530-560.

Fowler, L. D., and D. A. Randall, 1996 b: Liquid and Ice Cloud Microphysics in the CSU General Circulation Model. Part 3: Sensitivity tests. *J. Climate*, **9**, 561-586.

Ghan, S. J., L. R. Leung, and J. McCaa, 1999 a: A comparison of three different modeling strategies for evaluating cloud and radiation parameterizations. *Mon. Wea. Rev.* (in press).

Ghan, S. J., K.-M. Xu, D. A. Randall, R. Cederwall, D. G. Cripe, J. J. Hack, S. Iacobellis, S. Klein, S. Krueger, U. Lohmann, J. Pedretti, A. Robock, L. Rotstayn, R. Somerville, G. Stenchikov, Y. Sud, G. Walker, S. Xie, J. Yio, and M. Zhang, 1999 b: An intercomparison of single column model simulations of summertime midlatitude continental convection. Submitted to *J. Geophys. Res.*

Grell, G. A., Y.-H. Kuo, and R. Pasch, 1991: Semiprognostic tests of cumulus parameterization schemes in the middle latitudes. *Mon. Wea. Rev.*, **119**, 5-31.

Hack, J. J., and J. Pedrettii, 1999: Assessment of solution uncertainties in single-column modeling frameworks. *J. Climate* (in press).

Harshvardhan, R. Davies, D. A. Randall, and T. G. Corsetti, 1987: A Fast Radiation Parameterization for Atmospheric Circulation Models. *J. Geophys. Res.*, **92**, 1009 - 1016.

Held, I. M., R. S. Hemler, and V. Ramaswamy, 1993: Radiative-convective equilibrium with explicit two-dimensional moist convection. *J. Atmos. Sci.*, **50**, 3909-3927.

Hudlow, M. D., and V. L. Patterson, 1979: GATE radar rainfall atlas. *NOAA Special Report*, 155 pp.

Kao, C.-Y. J., and Y. Ogura, 1987: Response of cumulus clouds to large-scale forcing using the Arakawa-Schubert cumulus parameterization. *J. Atmos. Sci.*, **40**, 2138-2147.

Krueger, S. K., 1988: Numerical simulation of tropical cumulus clouds and their interaction with the subcloud layer. *J. Atmos. Sci.*, **45**, 2221-2250.

Krueger, S. K., G. T. McLean, and Q. Fu, 1995: Numerical simulation of the stratus-to-cumulus transition in the subtropical marine boundary layer. Part I: Boundary-layer structure. *J. Atmos. Sci.*, **52**, 2839-2850.

Krueger, S. K., G. T. McLean, and Q. Fu, 1995: Numerical simulation of the stratus-to-cumulus transition in the subtropical marine boundary layer. Part II: Boundary-layer circulation. *J. Atmos. Sci.*, **52**, 2851-2868.

Leach, M. J., J. Yio, and R. T. Cederwall, 1996: Estimation of Errors in Objectively Analyzed Fields and Sensitivity to Number and Spacing of Stations. *Proceedings of the Sixth Annual Atmospheric Radiation Measurement (ARM) Science Team Meeting*, San Antonio, TX., DOE CONF-9603149, 149-151. (Available from the U.S. Dept. of Commerce, Technology Administration, National Technical Information Service, Springfield, VA 22161, (703) 487-4650.)

Leach, M. J., J. Yio, and R. T. Cederwall, 1997: Improvements in the LLNL Objective Analysis Scheme for Deriving Forcing Fields for Single-Column Models Using ARM Data. *Proceedings of the Seventh Annual Atmospheric Radiation Measurement (ARM) Science Team Meeting*, San Antonio, TX. DOE CONF-970365, 263-266. (Available from the U.S. Dept. of Commerce, Technology Administration, National Technical Information Service, Springfield, VA 22161, (703) 487-4650.)

Lin, X., and R. H. Johnson, 1996 a: Kinematic and thermodynamic characteristics of the flow over the western Pacific warm pool during TOGA COARE. *J. Atmos. Sci.*, **53**, 695-715.

Lin, X., and R. H. Johnson, 1996 b: Heating, moistening, and rainfall over the western Pacific warm pool during TOGA COARE. *J. Atmos. Sci.*, **53**, 3367-3383.

Lord, S. J., 1982: Interaction of a cumulus cloud ensemble with the large-scale environment. Part III. Semi-prognostic test of the Arakawa- Schubert cumulus parameterization. *J. Atmos Sci.*, **39**, 88-103.

Lorenz, E. N., 1963: Deterministic non-periodic flow. *J. Atmos. Sci.*, **20**, 130-141.

Mace, G. G., and T. P. Ackerman, 1996: Assessment of error in synoptic-scale diagnostics derived from wind profiler and radiosonde network data. *Mon. Wea. Rev.*, 124, 1521-1534.

Nakajima, K., and T. Matsuno, 1988: Numerical experiments concerning the origin of cloud clusters in the tropical atmosphere. *J. Meteor. Soc. Japan*, **66**, 309-329.

Ooyama, K., 1987: Scale-controlled objective analysis. *Mon. Wea. Rev.*, **115**, 2476-2506.

Pan, D.-M., and D. A. Randall, 1998: A cumulus parameterization with a prognostic closure. *Quart. J. Roy. Meteor. Soc.*, **124**, 949-981.

Petch, J. C., and J. Dudhia, 1998: The importance of the horizontal advection of hydrometeors in a single-column model. *J. Climate*, **11**, 2437-2452.

Randall, D. A., and D.-M. Pan, 1993: Implementation of the Arakawa-Schubert cumulus parameterization with a prognostic closure. In *Cumulus Parameterization*, a Meteorological Monograph published by the American

Meteorological Society, K. Emanuel and D. Raymond, Eds., pp. 137 - 144.

Randall, D. A., Q. Hu, K.-M. Xu, and S. K. Krueger, 1994: Radiative-Convective Disequilibrium. *Atmos. Res.*, **31**, 315-327.

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

Randall, D. A., P. J. Sellers, J. A. Berry, D. A. Dazlich, C. Zhang, G. J. Collatz, A. S. Denning, S. O. Los, C. B. Field, I. Fung, C. O. Justice, C. J. Tucker, and L. Bounoua, 1996 b: A Revised Land-Surface Parameterization (SiB2) for Atmospheric GCMs. Part 3: The Greening of the CSU General Circulation Model. *J. Climate*, **9**, 738-763.

Randall, D. A., and D. G. Cripe, 1999: Alternative Methods for Specification of Observed Forcing In Single-Column Models and Cloud System Models. *J. Geophys. Res.* (to appear).

Redelsperger, J. L., P. Brown, F. Guichard, C. Hoff, M. Kawasima, S. Lang, T. Montmerle, K. Nakamura, K. Saito, C. Seman, and W. K. Tao, 1998: A GCSS model intercomparison for a tropical squall line observed during TOGA-COARE. Part I: Cloud Resolving Models. Submitted to *Quart. J. Roy. Meteor. Soc.*

Reed, R. J., D. C. Norquist, and E. Recker, 1977: The structure and properties of African wave disturbances as observed during Phase III of GATE. *Mon. Wea. Rev.*, **105**, 317-333.

Rennó, N. O., K. A. Emanuel, and P. H. Stone, 1994: Radiative-convective model with an explicit hydrologic cycle, 1, Formulation and sensitivity to model parameters. *J. Geophys. Res.*, **99**, 14429-14442.

Stokes, G. M., and S. E. Schwartz, 1994: The Atmospheric Radiation Measurement (ARM) Program: Programmatic background and design of the Cloud and Radiation Test Bed. *Bull. Amer. Meteor. Soc.*, **75**, 1201-1221.

Sui, C.-H., K.-M. Lau, W.-K. Tao, and J. Simpson, 1994: The tropical water cycle and energy budget in a cumulus ensemble model. Part 1: Equilibrium climate. *J. Atmos. Sci.*, **51**, 711-728.

Thompson, R. M., S. W. Payne, E. Recker, and R. J. Reed, 1979: Structure and properties of synoptic scale wave disturbances in the Intertropical Convergence Zone of the eastern Atlantic. *J. Atmos. Sci.*, **36**, 53-72.

Trenberth, K. E., and J. G. Olson, 1988: An evaluation and intercomparison of global analyses from the National Meteorological Center and the European Centre for Medium Range Weather Forecasts. *Bull. Amer. Meteor. Soc.*, **69**, 1047-1057.

Xu, K.-M., A. Arakawa, and S. K. Krueger 1992: The macroscopic behavior of cloud ensembles simulated by a cloud ensemble model. *J. Atmos. Sci.*, **49**, 2402-2420.

Xu, K.-M., and D. A. Randall, 1996 a: A semi-empirical cloudiness parameterization for use in climate models. *J. Atmos. Sci.*, **53**, 3084-3102.

Xu, K.-M., and D. A. Randall, 1996 b: Evaluation of statistically based cloudiness parameterizations used in climate models. *J. Atmos. Sci.*, **53,** 3103-3119.

Yamazaki, M., 1975: A numerical experiment of the interaction between cumulus convection and larger-scale motion. *Papers in Met. and Geophys.*, **26**, 63-91.

Yanai, M., S. K. Esbensen, and J.-H. Chu, 1973: Determination of bulk properties of tropical cloud clusters from large-scale heat and moisture budgets. *J. Atmos. Sci.*, **30**, 611-627.6

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