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Final Report

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Diagnostic Modeling of the ARM Experimental Configuration

Richard C. J. Somerville, P. I.

1. Overview and summary

ARM is the main focus of my research. I have been an ARM P. I. since the beginning of the program and have been a member of the ARM Science Team Executive Committee during this grant period. I have participated in all the Science Team meetings, have published in all the Science Team meeting reports, have helped draft the ARM Science Plan, and have otherwise been active in a broad range of ARM activities. The following list of significant publications summarizes the main accomplishments during the period of support of this ARM grant. In addition to the evidence of research productivity, I would like to point out two somewhat unusual accomplishments represented in this list. One is the DOE report by Somerville and Gautier (1995), which is a report of an invitational two-week conference which we organized on cloud-radiation feedbacks. This meeting, held at the Aspen Global Change Institute (AGCI), was attended by many ARM P.I.s. The conference report is an up-to-date summary of the field, and DOE has reprinted it as an ARM report. The second unusual accomplishment is my book, *The Forgiving Air: Understanding Environmental Change* (University of California Press, 1996). This book explains atmospheric global change issues for the general public. It is intended to be reader-friendly, with no mathematics or diagrams, and includes a glossary and an annotated bibliography. In addition to detailed coverage of ARM-related topics such as the greenhouse effect, climate modeling, and cloud-radiation feedbacks, the book covers ozone depletion, acid precipitation, air pollution, and energy, population and policy implications. I hope members of Congress and their staff will read this book before voting on the ARM budget.

A major accomplishment of our work during this grant period was to demonstrate the viability of using *in-situ* data in both mid-continent North America (SGP CART site) and Tropical Western Pacific (TOGA-COARE) locations to provide the horizontal advective flux convergences which force and constrain the Single-Column Model (SCM) which is the main theoretical tool of this work. I have used TOGA-COARE as a prototype for the ARM TWP site. Thus, we now know that SCMs can produce realistic budgets over the ARM sites without relying on parameterization-dependent operational numerical weather prediction objective analyses. Enclosed as an integral part of this report is a major paper which summarizes these results (Lee et al., 1997). This milestone paper lays the groundwork for much future research with SCMs, including AMIP-like intercomparisons of identically-forced SCMs. Among other noteworthy research results, I

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would cite the application of our stochastic theory (Malvagi et al., 1993) to the excess solar radiation absorption problem (Byrne et al., 1996). We will be working in the future to develop GCM parameterizations based on this approach. Finally, I note with special pride the 1994 paper based on the Ph. D. thesis of my student Waliser, which I think definitively solves a classical problem, the location of the ITCZ, the most conspicuous convective cloud feature on Earth.

Before the first SCM was built and tested, a legitimate question was whether the observational data would be sufficient to guarantee the verisimilitude and realism of the model results. That is, are boundary flux convergence observations sufficient to constrain the column budgets of heat, water and momentum? The answer is yes. Our experience demonstrates that direct observational sounding data from the SGP CART site can be used to provide the needed horizontal flux convergence forcing terms, thus obviating the need to use model-dependent operational numerical weather prediction (NWP) analyses. Essentially, we perform a line integral using sounding data from the boundaries of the SGP CART site. We have shown that this method provides accurate horizontal flux convergences.

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cont'd / The single-column model is diagnostic rather than prognostic. It is numerically integrated in an initial value problem which is forced and constrained by observational data. The input is an observed initial state, plus observationally derived estimates of the time-dependent advection terms in the conservation equations, provided at all model layers. Its output is a complete heat and water budget, including temperature and moisture profiles, clouds and their radiative properties, diabatic heating terms, surface energy balance components, and hydrologic cycle elements, all specified as functions of t_i . These model products can then be validated against ARM observations. This validation provides a test of the realism of the model physical parameterizations and a means of evaluating proposed improvements. In addition, it allows an assessment of the sensitivity of the results to individual elements of the parameterizations.)

These SCM results should be interpreted in light of the original motivation and purpose of ARM and its goal to improve the treatment of cloud-radiation interactions in climate models.) early GCMs, clouds were treated in a very simplistic way, and their ability to undergo changes, and thus to influence climate variability, was limited. In some models, in fact, clouds and their radiative properties were prescribed once and for all and then held constant, so that no feedbacks were possible. Later models, by contrast, featured clouds which could and did change their absolute amount and their height distribution in response to changes in atmospheric water vapor content. As the simulated clouds changed, so did their ability to contribute to both planetary reflectivity, or albedo, and to the greenhouse effect. For example, higher clouds are colder than lower clouds and thus less effective infrared emitters, and they are generally also optically thinner and thus less effective reflectors in the visible part of the spectrum. An increase in the average height of clouds, which tends to occur in many GCMs in response to a climate warming, therefore induces a positive feedback which augments the warming. It is this type of feedback which first made some GCMs much more sensitive than others to increasing carbon dioxide. However, it is clear now that we still cannot say confidently whether the sensitivity of these models is realistic. However, we do know that clouds and their effects are largely responsible for inter-model sensitivity differences.

ARM is a frontal assault on this dilemma. It is an imaginative effort to accelerate the improvement of GCM parameterizations. Its major thrust is to provide much of the badly needed empirical foundation for such parameterizations. ARM observations can provide invaluable information for the development of improved parameterizations. These data can include simultaneous measurements of cloud properties and radiation budget components. Such measurements will permit the validation of GCM parameterizations using actual physical conditions rather than hypothetical ones. The SCM is a tool to help accomplish this. Early in the development of the program, it was recognized that ARM should aim to provide major improvements in establishing the characterization of clouds, once they are formed in GCMs, i.e., in determining

their radiative properties. However, the equally important problem of enabling GCMs to simulate when and where clouds occur seemed more intractable. As the original ARM Program Plan acknowledged, "the prospects for contributing to improved parameterization of cloud formation itself are less certain." Indeed, it is clear that both topics, cloud formation as well as cloud characterization, need to be addressed, in order to make significant progress in improving GCM treatments of the cloud-radiation problem. Our results show clearly that SCMs can help establish the ability of modern parameterizations to handle cloud formation as well as cloud characterization.

2. Ongoing work and future research plans

- *Diagnostic modeling.* We plan to continue to evaluate systematically the ability of the model to provide realistically balanced heat and moisture budgets for the ARM experimental configuration. We shall begin by focusing on the SGP site, and we shall use TWP data when that site becomes operational. We shall explore the sensitivity of the results to choices in setting "tunable" model parameters. We shall conduct comparative studies of the relative merits of competing parameterizations. We are especially interested in assessing the relative merits of the approaches taken by different GCM groups. For example, does carrying cloud liquid water as a prognostic variable offer real advantages in terms of being able to specify cloud radiative properties realistically? Or is it feasible to specify these properties directly from the other large-scale GCM variables? Through addressing this type of question, ARM data can contribute directly to making progress on understanding and modeling cloud-radiation interactions. As is well known, these interactions give rise to feedbacks which comprise the single most serious source of uncertainty in GCM estimates of climate change due to increasing concentrations of greenhouse trace gases. They are also critical on shorter (e. g., ENSO) time scales. Our proposed diagnostic modeling effort is intended both to help test existing GCM parameterizations and to guide the development of future ones. We shall also carry out analyses to explore the degree to which *in situ* observations such as those from the boundary soundings at the SGP CART site can provide trustworthy flux convergence estimates. Are the budgets cited in our results in this proposal typical or exceptional, and can we optimally combine the *in situ* measurements with operational NWP analyses to improve our forcing data?

We also propose to carry out sensitivity tests: How sensitive is the surface heat flux balance to the different cloud parameterizations? Does inclusion of liquid water significantly affect the magnitude of the individual terms, or the sum of the terms? There are many tunable parameters in both the Smith and the Sundqvist cloud water schemes. We plan to use ARM measurements to optimize these parameters and to estimate the sensitivity of other diagnostic model results to these parameters. We already have a substantial amount of processed ARM data in a form suitable for ingestion by our software. As observations continue, we shall make use of new intensive observing periods (IOPs) and of efforts to incorporate new data streams to provide a more complete description of the atmosphere over the ARM site.

- *GCM experiments and observations.* As mentioned earlier, single-column model results taken in isolation can be potentially misleading, because the interaction between model domain and external forcing is one-way, with no possibility of feedback from the SCM onto the external forcing which drives and constrains it. We regard the SCM as one of a hierarchy of models, and we combine our SCM work with GCM research (e.g., Lee and Somerville, 1996). For example, we can use the GCM to evaluate the feedback just mentioned, and we can test the effect of parameterization changes on GCM climate sensitivity. We plan to use our GCM, which we have created by substituting alternative parameterizations for those of the R15 workstation version of the NCAR CCM2, to test a suite of alternative cloud-radiation algorithms. We also expect to update this GCM in the near future with improvements made by NCAR in CCM3. Our main

methodology relies on perpetual July integrations forced by constant SST perturbations. The single-column diagnostic model provides an ideal tool, in conjunction with ARM observational data. The Southern Great Plains CART site has begun to provide these measurements for a period that will eventually extend over a duration of several years. We plan to incorporate current and new GCM cloud parameterizations in our single-column diagnostic model, to intercompare them with one another, and to validate them against the observational data. The tested parameterizations will include relative humidity-based clouds and several versions of schemes involving a prognostic cloud water budget. We have already carried out extensive sensitivity tests with these parameterizations, in which we have examined the effect of varying tunable constants and other arbitrary aspects of the schemes. We shall compare the GCM results with ERBE data and with observations from ARM at the SGP CART site, diagnosed using the single-column model.

In general, our preliminary results show that the parameterizations with computed radiative properties tend to give qualitatively different cloud feedbacks (for both solar and terrestrial radiation) when compared to parameterizations based on relative humidity clouds with fixed radiative properties. Unfortunately, it is not known which cloud-radiation parameterizations are most realistic, or even if any current scheme captures the essential feedback processes of actual clouds. There is thus a clear need to intercompare these approaches with one another, and, even more importantly, to validate them against observations, so as to evaluate the strengths and weaknesses of each. The single-column diagnostic model provides an ideal tool for doing this, in conjunction with observational data for validation and with GCM experimentation. We shall validate surface flux fields as well as radiation.

- *Code development.* One technical goal is to create a version of the single-column model in which all the parameterizations can be selected simply by setting a switch, in the same way in which we have already incorporated leading moist convection parameterizations. Then we can use observational data systematically to test different parameterizations within the model, so as to determine clearly those respects in which any given parameterization does or does not conform to reality. Because the single-column model output is a complete heat and water budget for the atmospheric column, including time-dependent profiles of diabatic heating terms, surface energy balance components, and hydrologic cycle elements, validation against observational data can clearly reveal both realistic aspects and shortcomings of parameterizations such as the Smith and Sundqvist cloud water routines, as well as algorithms for latent and sensible heat fluxes in the lower atmosphere other than those taken into account by the convection schemes. We are also planning a systematic test of our procedure of relaxing or "nudging" the computed SCM temperature and moisture profiles toward the observed values, preventing an unrealistic secular trend or "drift." Until now, we have converged on a relaxation time scale of 24 hours by intuition and numerical experiment. We would like to put this aspect of our modeling technique on a firmer theoretical basis.

- *Cloud microphysics.* Recent observational work has provided promising suggestions for parameterizations which include the particle size distribution or effective radius of cloud liquid or ice particles. After the total water content, cloud particle size distribution is thought to be the single most important cloud microphysical parameter in determining cloud radiative properties. It is straightforward to incorporate suggested functional forms into the single-column model (SCM) algorithm, and to test the resulting radiative effects against measurements. We plan to give this type of parameterization development and validation high priority in the immediate future. We also plan to explore two promising new areas. One is to add to our SCM and test the Tiedtke liquid water scheme used in the current ECMWF model. The second is to use both the SCM and the GCM to explore the importance of including advection of cloud liquid water. Conventional wisdom is to neglect this process, but that simplification may not be permissible in all situations.

- *Stochastic radiative transfer parameterization development.* We shall also use ARM data diagnosed with our single-column model, in conjunction with atmospheric GCM experiments, to

develop and test a new class of alternative cloud-radiation parameterizations. We shall use the GCM which we developed from a low-resolution (15-wave rhomboidal) workstation version of the NCAR Community Climate Model, Version 2 (CCM2). As mentioned above, we have replaced most of the main NCAR parameterizations in CCM2 with our own, while retaining the adiabatic inviscid kernel and numerics of CCM2. The tested parameterizations include relative humidity-based clouds and several prognostic cloud water budget schemes. We shall emphasize testing stochastic approaches to cloud-radiation parameterization, based on the theory we recently developed (Malvagi et al., 1993). We shall carry out sensitivity tests with these parameterizations, in which we examine the effect of varying the schemes. We plan to use cloud pictures from the whole-sky imager at the SGP CART site, together with UAV aircraft measurements (if available) and possibly satellite imagery (if the resolution is fine enough) to estimate spatial cloud characteristics for input into the stochastic cloud routine. These measurements can provide probability distributions of cloud size and cloud spacing to characterize the macroscale structure of the cloud field.

- *Validation of satellite remote sensing inferences.* The widely accepted conjecture that cloud water content should increase with temperature has recently been called into question. The debate until now has been framed largely in terms of determining the magnitude and sign of the "f parameter" which I first defined in a paper with my student Remer in 1984 and which expresses the dependence of cloud liquid water (or, with simplifying assumptions, of cloud optical depth) on temperature. Satellite data show that f can apparently be negative, and recent work by Del Genio and others has helped to explain why this may be so. Comparison of model algorithms with measurements can help resolve this important issue. Single-column diagnostic models are an important tool to make such comparisons possible.

- *Exploration of the anomalous absorption issue.* Recently, we have applied the stochastic treatment to the well-known problem of explaining anomalous absorption of solar radiation in a cloudy atmosphere. We tentatively find that the stochastic treatment of cloud-cloud interactions yields a sufficiently long mean photon path length to explain much of the discrepancy recently reported between observations and GCM results. This work has recently been published (Byrne, et al., 1996). We plan to explore a larger region of parameter space more systematically than has been possible thus far.

3. Selected Recent Publications From ARM Support

(This list omits secondary items such as ARM Science Team reports, published abstracts, most conference proceedings, oral presentations, etc.)

Malvagi, F., R. N. Byrne, G. C. Pomraning, and R. C. J. Somerville, 1993: Stochastic radiative transfer in a partially cloudy atmosphere. *Journal of the Atmospheric Sciences*, **50**, 2146-2158.

Somerville, R. C. J., and S. F. Jacobellis, 1994: Diagnostic analysis of cloud radiative properties. *Preprint from the Fifth Symposium on Global Change Studies*, American Meteorological Society, January 23-28, 1994, Nashville, TN, 11-14.

Somerville, R. C. J., 1994: Review of "Aerosol-Cloud-Climate Interactions." P. V. Hobbs (ed.) Academic Press, San Diego, CA, 1993. xii, 233 pp., illus., *Science*, **264**, 115.

Iacobellis, S. F., R. Frouin, H. Razafimanilo, R. C. J. Somerville, and S. C. Piper, 1994: North African savanna fires and atmospheric carbon dioxide. *Journal of Geophysical Research*, **99**, 8321-8334.

Waliser, D. E., and R. C. J. Somerville, 1994: The preferred latitudes of the intertropical convergence zone. *Journal of the Atmospheric Sciences*, **51**, 1619-1639.

Somerville, R. C. J., and S. F. Iacobellis, 1994: Monsoon mechanisms: Single-column diagnostic modeling. *Proceedings of the International Conference on Monsoon Variability and Prediction*, International Centre for Theoretical Physics, Trieste, Italy, 9-13 May 1994, 593-600.

Lee, W.-H., and R. C. J. Somerville, 1995: Testing parameterizations of cloud-radiation feedbacks. *Preprint from the Symposium on the Regulation of Sea Surface Temperatures and Warming of the Tropical Ocean Atmosphere System*, American Meteorological Society, Jan. 15-20, 1995, Dallas, 69-72.

Somerville, R. C. J., and C. Gautier, 1995: Elements of Change 1994 - Climate-Radiation Feedbacks: The Current State of the Science. DOE/ER-0661T, 123 pp.

Byrne, R. N., R. C. J. Somerville and B. Subasilar, 1996: Broken-cloud enhancement of solar radiation absorption. *Journal of the Atmospheric Sciences*, **53**, 878-886.

Lee, W.-H., and R. C. J. Somerville, 1996: Effects of alternative cloud radiation parameterizations in a general circulation model. *Annalae Geophysicae*, **14**, 107-114.

Somerville, R. C. J., 1996: *The Forgiving Air: Understanding Environmental Change*. University of California Press, xiv + 195 pp.

Somerville, R. C. J., S. F. Iacobellis and W.-H. Lee, 1996: Effects of cloud-radiation schemes on climate model results. *World Resource Review*, **8**, 321-333.

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

Lee, W.-H., S. F. Iacobellis, and R. C. J. Somerville, 1997: Cloud-radiation forcings and feedback: General circulation model tests and observational validation. *Journal of Climate*, **10**, 2479-2496.

Isakari, S. M., and R. C. J. Somerville, 1997: Numerically efficient radiative-convective models. *Journal of Climate*, submitted.