Investigating Cloud Radiative Forcing in the Tropical West Pacific Using a Single-Column Model

J. C. Petch and J. T. Kiehl
National Center for Atmospheric Research
Boulder, Colorado

Introduction

The Tropical Western Pacific (TWP) is an important region for world climate (Webster and Lucas 1992) and was the subject of the Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (TOGA-COARE) in 1992/3. This experiment included an intensive observational period (IOP) from November 1992 through March 1993, which provided observations suitable for creating datasets that can be used for forcing either single-column models (SCMs) or cloud-resolving models (CRMs).

Organized cloud systems in the TWP have a major impact on radiation. The accurate representation of these cloud systems and their interaction with radiation in large-scale models is of great importance. CRMs have been extensively used as a diagnostic tool to study these cloud systems (e.g., Wu et al. 1997) with the hope that they can improve our physical understanding of these systems and provide information to improve larger-scale climate models. SCMs provide a useful link from cloud-resolving models to climate models. SCMs can be forced with the same dataset as CRMs and the results compared with observations and results from CRMs; the links between these types of models and observations are discussed in Randall et al. (1996).

The Experiment

SCCM3 is a single-column version of the National Center for Atmospheric Research's Community Climate Model (CCM3), which was developed with support from the U.S. Department of Energy (DOE) Computer Hardware, Advanced Mathematics, and Model Physics (CHAMMP) Program. In this work, SCCM3 is forced with 39 days of data from the TOGA-COARE IOP; this is the same time period used by Wu et al. (1997). The forcing data are the objectively analyzed TOGA-COARE sounding data averaged over the Intensive Flux Array (IFA) (Lin and Johnson 1996), with profiler wind observations included (Ciesielski et al. 1996).

In some initial experiments, SCCM3 was allowed to predict temperature and moisture freely. However, due to the deep convection scheme (described in Zhang and McFarlane 1995) drying the lower troposphere, the model predicted unrealistic temperature and moisture profiles (out by up to 20 K and 20 gkg^{-1}). The unrealistic temperature and moisture profiles were inconsistent with those seen in the full model, where large-scale dynamical feedbacks prevented such unrealistic profiles from existing. Hence, the cloud properties did not represent those of the full model, and any experiments into cloud radiative forcing using SCCM3 are somewhat meaningless. To overcome this problem, the model temperature and moisture fields were relaxed to the observed values on a 6-hour time scale, which kept temperatures and specific humidities within 2 K and 2 gkg^{-1} of the observed values, respectively. This kept the cloud radiative properties much more consistent with the full model (see results section).

Relaxation of temperature and moisture to observations clearly introduces strong constraints to the column model simulations. The need for relaxation points out problems either in the model's physical parameterizations and/or the forcing data. Identification of the sources of these problems requires further investigation.

For this report, we focus on the influence of clouds on the top of the atmosphere (TOA) radiative fluxes. Results from SCCM3 are compared with satellite-derived values of albedo and outgoing longwave radiation (OLR). Also, the ability of the model to reproduce the observed near cancellation of longwave and shortwave cloud radiative forcing (LWCF and SWCF) shown in Kiehl (1994) is investigated. A statistical approach is adopted to investigate the relationship between shortwave and longwave cloud radiative properties. Thus, the simulations are not expected to reproduce the specific time evolution of the observations. Agreement of the statistical behavior of CCM3 with the SCM lends credibility to the use of the SCM for studying the physical processes relevant to the full CCM.

Sensitivity experiments are carried out to investigate how TOA radiative fluxes change when different cloud schemes are included in SCCM3. In one experiment, a one-category prognostic microphysical scheme described by Rasch and Kristjansson (1997) replaces the diagnostic cloud scheme. In a second experiment, a five-category bulk microphysical scheme (Swann 1994) designed for use in a mesoscale model is included into SCCM3. This scheme is very similar to the one Fowler et al. (1996) included in a climate model.

Results

Although not shown here, all the versions of SCCM3 used in this experiment reproduced the overall trends seen in the International Satellite Cloud Climatology Project (ISCCP) OLR data (Zhang et al. 1995; Rossow and Zhang 1995) and GMS-4 albedos (Collins, personal communication) very well. Systematic differences between observations and the model in the 39-day mean were most noticeable and most significant, as the differences in the long-term mean will have the largest impact on the simulation of the climate in the full model. This being true, it means that we can focus on the 39-day mean values of albedo and OLR to investigate how well the model is doing in predicting the TOA radiative fluxes; these are shown in Table 1.

From Table l, it can be seen that SCCM3 reproduces the mean albedo very well, but significantly underpredicts the OLR. However, when the one-category microphysical scheme is included, the albedo prediction is still good and the predicted OLR is much better. The five-category scheme does less well than either the standard model or the one-category scheme, but it should be noted that both the standard CCM3 and the one-category scheme had free parameters tuned within the full model to give TOA radiative fluxes that are a good match to observations.

Table 1. 39 day mean values of TOA albedo and OLR from observations and various versions of SCCM3. The numbers in brackets represent the difference from observations.

Model Run	Albedo (%)	OLR (Wm^{-2})
Observed	28	215
SCCM3	29 (+1)	192 (-23)
1 Category	28 (0)	211 (-4)
5 Category	32 (+4)	191 (-24)
5 Category (0.7xcf)	29 (+1)	209 (-6)
CRM (Wu et al. 1997)	44 (+16)	184 (-31)

A method of "tuning" that is not related to the bulk microphysical scheme but can have the same effect as the tuning made to the one-category scheme is to use a different cloud fraction calculation. Although a completely different scheme is not used in the work described here, an adjustment to the current scheme is made to prove this point. When the cloud fraction prediction from the current scheme is multiplied by a factor of 0.7, the TOA radiative fluxes are closer to observations (see Table 1, 5 category [0.7xcf]).

The TOA fluxes in all runs of the SCM are much closer to the observations than the CRM. This may seem surprising, but the TOA energy balance is very important in climate modeling and physical parameterizations in climate models are often "tuned" to give reasonable agreement with observed TOA radiative fluxes. However, this does not really explain the discrepancies between the five-category scheme and the CRM, neither of which has been tuned in any way. One possibility is a problem with the cyclic boundary conditions in the CRM, as suggested in Wu et al. (1997).

Plots of the daily mean LWCF versus SWCF for various model runs and the observed values are shown in Figure 1. The observed values are calculated using the model predicted values for the clear sky; this is reasonable because the model does a very good job of predicting clear sky radiative fluxes (Kiehl et al. 1997).

The observed values of the daily mean LWCF and SWCF show a cancellation agreement as seen in the monthly mean Earth Radiation Budget Experiment data shown in Kiehl (1994). The SCCM3 [shown in (ii) of Figure 1] and output from an Atmospheric Model Intercomparison Project run of the full CCM3 [shown in (iii)] are in good agreement with each other, but do not match the observations well. The slope is too flat and there appears to be a curve to the distribution, with the LWCF larger than the SWCF for many of the points. As mentioned in the discussion of this experiment, SCCM3 does not agree with the full model if the temperatures are not relaxed to the observed values, and there is very little agreement at all between LWCF and SWCF (see [iv]).

Including the one-category microphysical scheme does improve the relation between LWCF and SWCF a little [see (v)], but there is still room for improvement. The same can be said about the five-category bulk microphysical scheme when the cloud fraction is reduced by a factor of 0.7 (see [vi]).

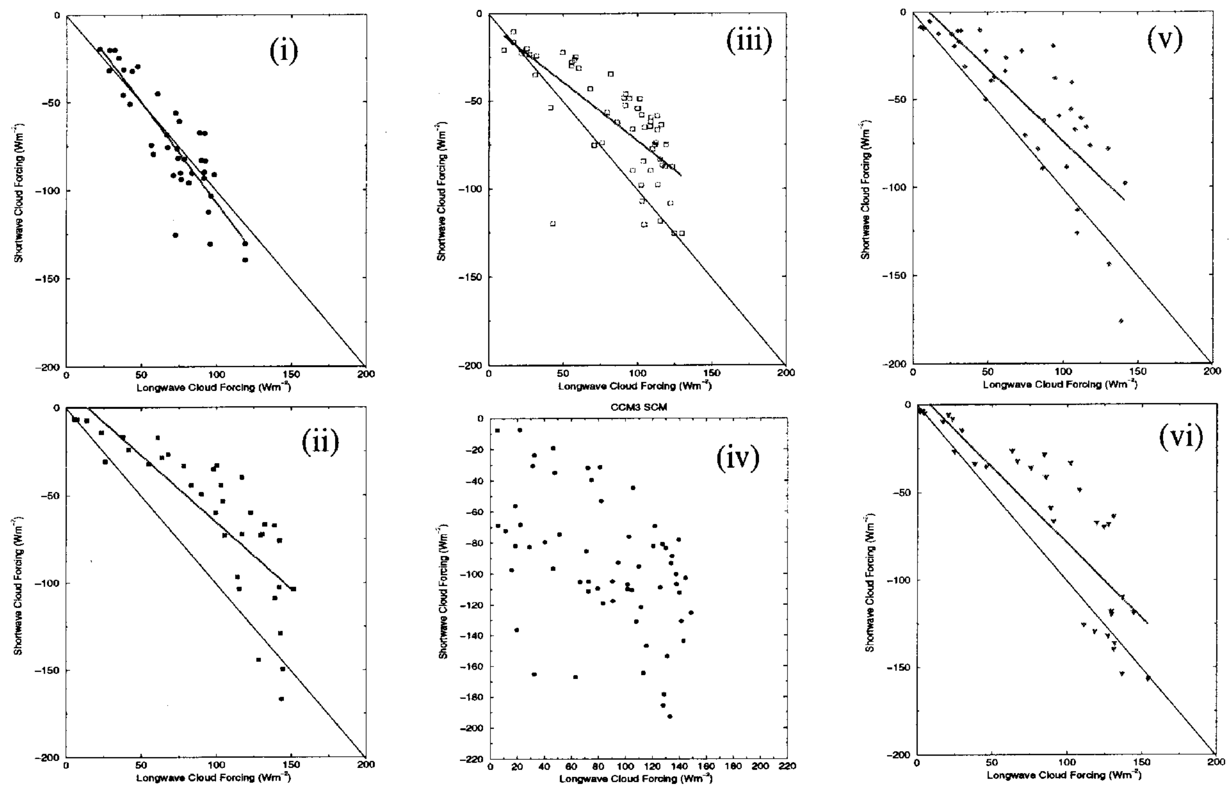

Figure 1. LWCF vs. SWCF for (I) Observations, (ii) SCCM3, (iii) CCM3, (iv) SCCM3 (unrelaxed), (v) 1-category microphysical scheme, (vi) 5-category microphysical scheme with 0.7xcf.

Summary

SCCM3, a single-column version of CCM3, has been forced with data collected during the TOGA-COARE IOP to investigate the model's ability to reproduce the correct TOA radiative fluxes and the relationship between LWCF and SWCF. The SCM had to be relaxed towards observed values of temperature and specific humidity to give results representative of the full model.

It was shown that SCCM3 reproduced the TOA albedo very well for a 39-day period of the TOGA-COARE IOP, but significantly underestimated the OLR. When a one-category microphysical scheme was included, the predicted albedo remained the same as the observations and the OLR improved to be much closer to the observed value. A more detailed five-category bulk microphysical scheme was also included, but this did not give a good prediction of either albedo or OLR. It was hypothesized that the five-category scheme may give better results if used with a different method of predicting cloud fraction. Although a different scheme was not tested in the work described here, the current cloud fraction prediction was multiplied by 0.7 to show that the five-category scheme could give reasonable TOA fluxes without adjustments or "tuning" to the microphysical conversion equations. In the future, a completely different cloud fraction scheme will be tested.

Acknowledgments

This work was funded by the U.S. Department of Energy's (DOE's) Atmospheric Radiation Measurement Program under grant DE-AI05-92ER61376. The SCM was developed by Jim Hack with support, in part, from CHAMMP grant DEAI05-92ER61471, which is administered by DOE's Office of Energy Research in the Environmental Science Division. The National Center for Atmospheric Research is operated by the University Corporation for Atmospheric Research under sponsorship of the National Science Foundation.

References

Ciesielski, P. E., R. H. Johnson, and L. M. Hartten, 1996: Impacts of merging profiler and rawinsonde winds on TOGA COARE analyses. Submitted to *J. Atmos. Oceanic Tech*.

Fowler, L. D., D. A. Randall, and S. A. Rutledge, 1996: Liquid and ice phase microphysics in the CSU GCM: Part 1. Model description and simulated microphysical processes. *J. Clim.*, **9**, 489-529.

Kiehl, J. T., 1994: On the observed near cancellation between longwave and shortwave cloud forcing in tropical regions. *J. Clim.*, **7**, 559-566

Kiehl, J. T., J. J. Hack, and J. W. Hurell, 1997: The energy budget of the NCAR Community Climate model (CCM3). Submitted to *J. Clim.*

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

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

Rasch, P. J., and J. E. Kristjansson, 1997: A comparison of the CCM3 model climate using diagnosed and predicted condensate parameterizations: Submitted to *J. Clim*.

Rossow, W. B., and Y-C. Zhang, 1995: Calculations of surface and top of atmospheric radiative fluxes from physical quantities based on ISCCP datasets, 2. Validation and first results. *J. Geophys. Res*., **100**, 1167-1197.

Swann H., 1994: *Cloud microphysical processes - A description of the parameterization used in the large eddy model*. JCMM Internal Report No. **10**, Joint Centre for Mesoscale Meteorology, U.K. Meteorological Office, Bracknell, Berkshire, U.K.

Webster, P. J., and R. Lucas, 1992: TOGA-COARE: The Coupled Ocean Atmosphere Response Experiment. *Bull. Amer. Meteor. Sci*., **73**, 1377-1416.

Wu, X., W. W. Grabowski, and M. W. Moncreif, 1997: Long-term evolution of cloud systems in TOGA COARE and their interactions with radiative and surface processes. Submitted to *J. Atmos. Sci.*

Zhang, G. J., and N. A. McFarlane, 1995: Sensitivity of climate simulations to the parameterization of cumulus convection in the Canadian Climate Centre general circulation model. *Atmos. Ocean*, **33**, 407-446.

Zhang, Y-C., W. B. Rossow, and A. A. Lacis, 1995: Calculations of surface and top of atmospheric radiative fluxes from physical quantities based on ISCCP datasets, 1. Method and sensitivity to input data uncertainties. *J. Geophys. Res*., **99**, 20815-20827.