13.7 ANALYSIS OF FORCING METHODS FOR SINGLE-COLUMN MODELS

Sam F. Iacobellis*, Richard C. J. Somerville and Dana E. Lane

Scripps Institution of Oceanography
University of California, San Diego

1. INTRODUCTION

The single-column model (SCM) is a diagnostic model resembling a single vertical column of a 3-dimensional general circulation model (GCM). The SCM includes physical parameterizations which are currently used in modern GCMs. Due to the one-dimensionality of the SCM, the horizontal advection of heat, moisture and momentum are supplied to the model from either observations or 3-dimensional numerical analyses. Single-column models are being used increasingly to both develop and evaluate parameterizations and are an integral component of the Atmospheric Radiation Measurement (ARM) Program research strategy.

Despite the rapid increase in the use of SCMs, there remain important questions in regards to the best method of forcing or "running" the SCM. A recent study has found that the temperature and humidity evolution from a particular SCM displayed significant sensitivity to perturbations in the initial conditions. It is not known if this sensitivity is unique to the particular model tested or is an inherent feature of all SCMs. An additional issue is that of relaxation. It is often desirable to perform model runs over periods of several days or more in order to sufficiently evaluate parameterization performance. Unfortunately, errors in the observational data used to force the model can at times lead to large errors in the model temperature and humidity profiles. In order to properly test and evaluate parameterizations it is sometimes necessary to apply a relaxation technique to insure that the model temperature and humidity profiles do not depart significantly from observations. Several alternative methods of relaxation, including re-initialization, are available and there appears to be no general consensus within the SCM community as to which method should be employed.

In this study, we utilize observational data from the ARM Southern Great Plains (SGP) site to investigate the above questions. In one experiment, a series of model runs are performed, each run containing a small random perturbation of the initial conditions. The results from these runs are used to examine the sensitivity of model results from our SCM to the initial conditions. The model results that we will present include the temperature, humidity, surface and TOA radiative flux budget evolution. We also performed several model runs using various methods of relaxation. The results from these runs are analyzed to determine the sensitivity of several model diagnostic quantities to the method of relaxation.

2. CONTROL VERSION OF SCM

The configuration of the single column model used in this study has 53 vertical layers and a timestep of 7.5 minutes. The control version of the SCM contains the longwave radiation parameterization of Morcrette (1990) and the solar radiation parameterization of Fouquart and Bonnel (1980). Cloud water and cloud amount are calculated using the formulation of Tiedtke (1993). The SCM employs the cumulus convection parameterization of Zhang and McFarlane (1995) and the scheme of Hack (1994) for shallow convection. This is the same cumulus convection parameterization package contained in the NCAR community climate model (CCM3). In this study, the land surface temperature and surface heat fluxes are specified from observations.

Numerical experiments were performed by applying the SCM in the atmospheric column directly over the ARM SGP site. The SCM was forced with horizontal advection tendencies and vertical velocities calculated using the constrained variational scheme of Zhang and Lin (1997). This forcing data was derived from measurements gathered by radiosondes and wind profilers at the ARM SGP site during the three week period Intensive Observing Period (IOP) in the Summer of 1995. We have assumed maximum overlap of clouds due to the strongly convective atmospheric environment at the ARM SGP site during summer.

3. SENSITIVITY TO INITIAL CONDITIONS

The sensitivity of our SCM to the initial conditions was examined by including randomly generated errors in the initial profiles of temperature (T) and specific humidity (q). A total of 50 model runs were performed. Each model run

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* *Corresponding author address*: Sam F. Iacobellis, Scripps Institution of Oceanography, 9500 Gilman Dr., Dept. 0224, La Jolla, CA 92093-0224.

utilized a slightly different set of initial conditions by including a random perturbation of +/- 1.0°C (T) and +/- 5% (q) in each model layer. No relaxation was used in these model runs.

Figure 1 shows the standard deviation of temperature (σ_T) at 900, 500, and 200 hPa from the 50 perturbation runs of the SCM using the Summer 1995 forcing data. The magnitude of σ_T generally increases as the model run progresses in time. The maximum σ_T for these perturbation runs is approximate 4°K. Maximum values of the specific humidity standard deviation (σ_q) (not shown) were 3.3 g kg^{-1}. Similar sets of perturbation runs have been performed using four other ARM IOP data sets (Fall 1994, Fall 1995, Spring 1996, and Summer 1997) and have in general yielded similar results. However, perturbation runs using the Fall 1994 forcing data yielded very low values of σ_T and σ_q. Additionally research is planned to help determine why this data set yielded low values of σ_T and σ_q.

SCMs are often used for sensitivity studies and parameterization development of cloud-radiation schemes. As a result, it is important to understand the effect that small perturbations in the initial conditions might have on cloud and radiative flux parameters. Figure 2 shows the standard deviation of cloud fraction (σ_{cld}), cloud ice/water path (σ_{cwp}), downwelling surface shortwave radiation (σ_{sol}), and outgoing longwave radiation (σ_{olr}) from the 50 perturbation runs using the Summer 1995 forcing data. Maximum values of σ_{cld} reach approximately 0.30 while σ_{cwp} reaches a maximum of 30 grams m^{-2}. Maximum values of σ_{cld} and σ_{cwp} do not necessarily occur at the same time since low clouds generally contain much more cloud ice/water than high clouds. As a result, one needs to consider both σ_{cld} and σ_{cwp} when interpreting the time series of σ_{sol} and σ_{olr}. Maximum values of σ_{sol} and σ_{olr} are 40 and 25 W m^{-2}, respectively. The magnitudes of both σ_{sol} and σ_{olr} indicate that small instrumental errors (represented here by the added perturbations) in the initial conditions may have significant effects on the values of model produced radiative fluxes. These results suggest that when using the SCM in a sensitivity study or during parameterization development, an ensemble of model runs be performed, each run using a slightly perturbed initial profile of temperature and humidity.

4. RELAXATION METHODS

As described Section 1, it is often desirable to maintain the model temperature and humidity profiles close to observed values using relaxation and/or re-initialization. When the SCM is operated using relaxation, the temperature and humidity profiles are relaxed to the observed profiles using a specified time scale, τ. The simplest application of relaxation is to set τ to a value constant at all heights. An alternative approach is relaxation advection where τ is calculated in each model layer as:

$$\tau = D \big/ 2\sqrt{u^2 + v^2}$$

where D is the distance across the SCM domain, and u and v are the horizontal wind components. The temperature and humidity profiles may also be re-initialized with observed values at a certain frequency.

Seven additional SCM runs were performed using various techniques described above to keep the model temperature and humidity profiles close to observed. All of these runs used the Summer 1995 forcing data. The first two of these runs used constant values of the relaxation time scale of 2 and 24 hours. The third run used relaxation advection. The last four runs used re-initialization with a 24-hour frequency, but with the re-initialization occurring at a different time of day (0000, 0600, 1200, and 1800 hours local time) in each run.

Figure 3 shows the RMS temperature differences (ΔT_{RMS}) (model - observed) for these seven runs. As expected, ΔT_{RMS} from the run with τ=2 hours is much smaller than with τ=24hours.

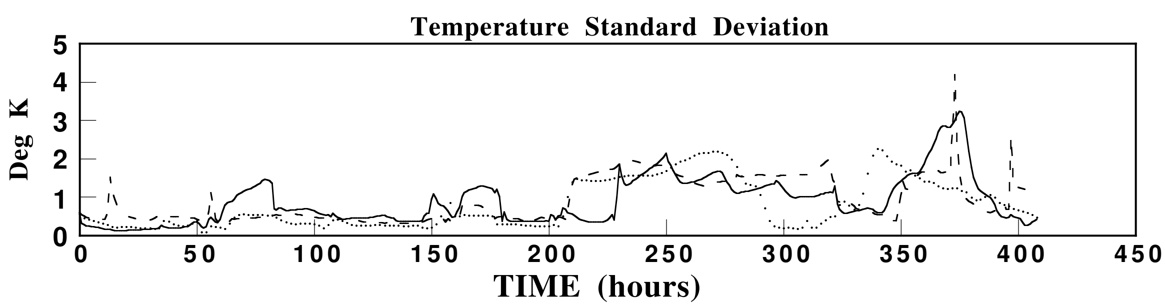

Figure 1. Standard deviation of temperature at 900 hPa (solid line), 500 hPa (dotted line) and 200 hPa (dashed line) from the 50 perturbation runs of the SCM for the Summer 1995 IOP.

The run using relaxation advection produced ΔT_{RMS} values less than the run with τ=24 hours, but larger than the run with τ=2 hours. Note that near the surface the values of ΔT_{RMS} from the relaxation advection run are much closer to those from the run with τ=24 hours. This is due to the relatively low wind speeds near the surface that result in a larger relaxation time scale compared to higher altitudes. The ΔT_{RMS} curves from the four re-initialization runs are very similar to one another with larger values near the surface. The magnitude of ΔT_{RMS} from these runs are very close to that from the τ=24 hour relaxation run. Near the surface, the value of ΔT_{RMS} from the runs re-initialized at 0000 and 1800 are about 1.5°K less than those re-initialized at 0600 and 1200 and may be related to the diurnal cycle of convection.

The mean cumulus mass flux profiles from these runs and the control run (no relaxation or re-initialization) are shown in Figure 4. From these curves it is apparent that there is a significant amount a variability in the cumulus mass flux depending on which relaxation or re-initialization technique is used. The run which re-initialized at 1800 produced significantly more cumulus mass flux than any of the other runs and again may be due to the timing of diurnal cycle of convection.

The results from these experiments illustrates some potential difficulties that may arise when using relaxation and/or re-initialization techniques. As shown here, the strength of the cumulus mass flux can be modified by simply altering the time of day at which the model temperature and humidity profiles are re-initialized. While the differences were not as large, the value of the relaxation time scale can also affect the strength of the cumulus mass flux.

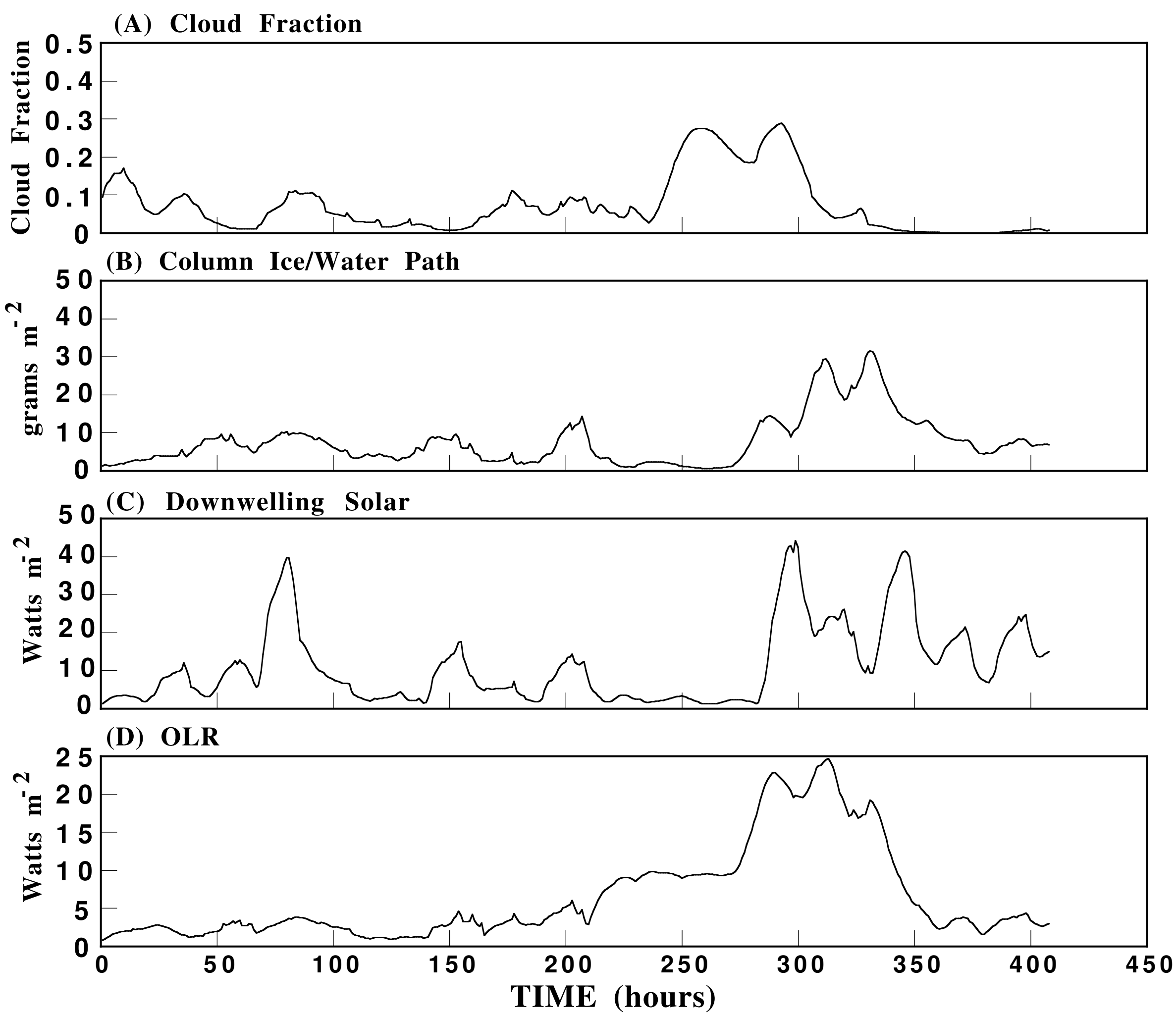

Figure 2. Standard deviation of a) cloud fraction; b) column ice/water path; c) downwelling surface shortwave flux; and d) outgoing longwave radiation from the 50 perturbation runs of the SCM for the Summer 1995 IOP.

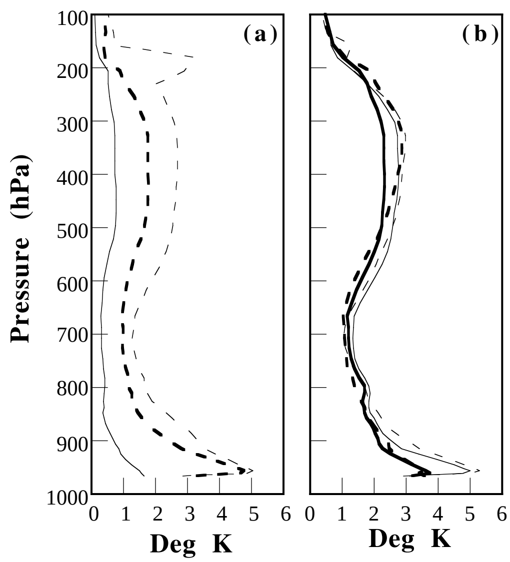

Figure 3. RMS temperature differences (model - observed). The curves in panel (a) are from the SCM runs that used 2-hr relaxation (thin solid); 24-hr relaxation (thin dashed); and relaxation advection (thick dashed). The curves in panel (b) are from the SCM runs that used 24-hour re-initialization at 00hr (thick solid); 06hr (thin solid); 12hr (thin dashed); and 18hr (thick dashed).

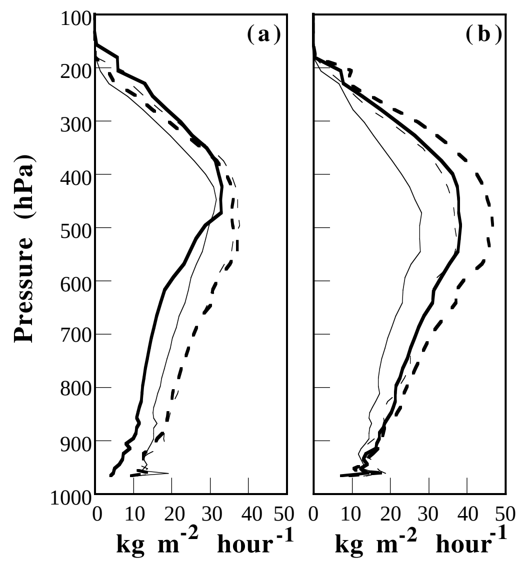

Figure 4. Mean model produced cumulus mass flux. The curves in panel (a) are from the SCM runs that used no relaxation (thick solid); 2-hr relaxation (thin solid); 24-hr relaxation (thin dashed); and relaxation advection (thick dashed). The curves in panel (b) are from the SCM runs that used 24 hour re-initialization at 00hr (thick solid); 06hr (thin solid); 12hr (thin dashed); and 18hr (thick dashed).

4. CONCLUSIONS

• SCM results are sensitive to perturbations in the initial profiles of T and q representative of typical instrument and measurement errors. The standard deviation of downwelling surface solar radiation at times approaches 40 W m^{-2}.

• Results from perturbation experiments suggests that ensemble of SCM runs should be performed when using the SCM for sensitivity studies or parameterization development. Future work will help determine the necessary number of ensemble runs.

• SCM results, such as the mean cumulus mass flux profile, are sensitive to the time of day at which model profiles of temperature and humidity are re-initialized.

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