P1.7

RESPONSE OF CONVECTION TO DRY LAYERS: SIMULATION AND PARAMETERIZATION TESTS

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1. INTRODUCTION

It has long been conjectured that growth of convection is slowed by entrainment of dry environmental air (e.g., Stommel 1947). Observations in the tropical Pacific (Brown and Zhang 1997) taken as part of the Tropical Ocean Global Atmosphere Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) (Webster and Lucas 1992) are consistent with this view. These data show depressed cloud top heights correlated with lower relative humidities. Parameterizations of convection for numerical models have attempted to account for this effect by incorporating sophisticated mixing schemes. The buoyancy sorting mechanism proposed by Raymond and Blyth (1986) has been applied in both the Kain – Fritsch (1990) mesoscale convective parameterization as well as the Emanuel (1991) convective parameterization. Testing of such parameterizations can be difficult. This difficulty owes to both the variety of convective conditions a useful parameterization needs to work in, as well as the lack of data available to test the schemes. One may expect a convective parameterization to be sensitive to the model grid resolution, thus increasing the amount of testing required. Observed datasets such as those available from the Atmospheric Radiation Measurement (ARM) Program (Stokes and Schwartz 1994) for testing of parameterizations in single column models are often not suitable for testing parameterizations at the relatively high resolution of current numerical weather prediction models. Testing of parameterizations in the context of forecast experiments is ultimately needed, but often does not provide the detailed information needed to accurately assess the performance of an isolated part of the forecast system, such as the convective parameterization.

With the above considerations in mind, an effort has been made to develop a system for controlled experiments of model physics parameterizations with the Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (CCAMPS) (Hodur 1997). The method employed is to run the COAMPS nonhydrostatic forecast model at high resolution where convection is resolved, or nearly so, generating data that can be used off-line for tests in either a single column model mode or a semi-prognostic mode. The reader is reminded that the difference between these two types of test is simply that in the semi-prognostic mode the atmospheric profile evolves as prescribed by input data, whereas in the single-column model mode, the atmospheric profile evolves as determined by the advective tendencies and the physics of the model. Petch and Dudhia (1998) have recently applied this technique for example in experiments with ARM data. This method has the obvious disadvantage of relying on model output for data. Of course there are several advantages as well. In such tests one knows precisely what the “true” atmospheric profile is, as well as the fluxes and precipitation, so the performance of the scheme can be accurately assessed. The horizontal resolution of the dataset used to run the physics tests can easily be modified, quite the contrary to observed data. In addition, the environment used for the initial cloud-resolving scale forecasts can be modified, allowing for a look at the ability of the parameterization to account for a specific change in the environment. This feature is exploited in the present work.

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2. DRY LAYERS IN THE TROPOSPHERE

An instructive example of the occurrence of dry layers in the atmosphere is the so-called “dry tongue” phenomenon observed in the tropical Pacific (Numaguti et. al. 1995). Dry tongues occur as extensive dry layers in the tropical atmosphere from low-levels to mid-levels. The horizontal scale is on the order of hundreds of kilometers, and the dry episodes persist for several days. Dry tongues generally have their origin in the Subtropics (Numaguti et al. 1995; Mapes and Zuidema 1996). Although named for the anomalously dry moisture profiles associated with the advection of subtropical air into the warmer, moister Tropics, dry tongues are also characterized by a sharp stable layer just below their base that may be caused by radiation (Mapes and Zuidema 1996).

3. SIMULATIONS

The study uses a series of nested quasi- cloud resolving model forecasts of convection in the tropical western Pacific carried out using a triple-nested version of COAMPS. The inner mesh in the COAMPS forecasts has a horizontal dimension of 3 km, allowing for a somewhat crude resolution of deep convective circulations. The forecasts were carried out for the region near the edge of a dry tongue in the western tropical Pacific in November 1998. The data needed to run the COAMPS forecasts for a TOGA COARE dry tongue case of interest are not available. The episode chosen is similar to one that occurred in November of 1992 during TOGA COARE in which dry air moved to the northeast from the Subtropics into the equatorial region. Several simulations were carried out for the November 1998 case. For the present work, because the 3-km mesh grid was centered near the edge of the dry tongue at 8^{o} S Lat. and 152^{o} E Long., the moisture sounding was not representative of the dry tongue itself. The 3-km mesh was situated in an area of deep convection, and by allowing dry air to advect into this mesh at mid- to upper-levels the impact on convection of enhanced evaporation could be investigated.

The COAMPS model was spun up over a 3-day period using the data assimilation system and a cycle time of 12 hours. The model was run with 30 vertical levels, and the 3-km mesh grid had 85 x 85 grid points in the horizontal. A 24-hour forecast beginning at 00 GMT on November 21, 1998 was initiated after the spinup period. In this forecast, a number of isolated deep convective cells break out in the 3-km mesh grid. The deepest of these penetrate to about the 150mb level. In order to investigate the effect of a dry layer on such convection, three more forecasts were carried out. To prepare for these forecasts, fields from the 00Z COAMPS forecast on November 20 were taken and used for a short, one-day spinup with modified lateral moisture boundary conditions on the 3-km mesh grid. For this spinup, a dry TOGA COARE moisture sounding (an average over the Intensive Flux Array (IFA) region from 00 GMT on November 14, 1992) was added as a lateral boundary condition to the 3-km mesh grid above 800 mb. The moisture was initialized to the TOGA COARE sounding above 800 mb. The three additional forecasts that were started 24 hours later (00Z on November 21, 1998) thus began with a dry sounding in mid- to upper levels. Of these three forecasts, the one that will be referred to here as Forecast A was carried out using lateral moisture boundary conditions for the 3-km mesh grid obtained from the parent 9-km mesh grid. In the second forecast, Forecast B, the lateral moisture (mixing ratio) boundary conditions were the same as A below 600 mb, but were set to the values from the TOGA COARE sounding above that level. In the third forecast, Forecast C, the moisture boundary conditions were treated the same as for Forecast B, except the threshold pressure level was changed from 600 mb to 800mb.

Forecast A looks similar to the initial forecast run without implementing the artificial boundary conditions for the 3-km mesh grid, though it has somewhat less rainfall. Results for forecasts A, B and C are shown in Fig. 1 for the simulated 3-km mesh mean mixing ratio of precipitating hydrometeors as it varied with forecast time. The simulated peak cloud top heights are not significantly affected by the dry layer in these forecasts, but the distribution of cloud top heights is skewed significantly toward shallower clouds for the drier soundings. This is perhaps more clear in plots of vertical mass flux (not shown). The surface precipitation in Forecast B is about 40 percent less than for A, consistent qualitatively with TOGA COARE observations of the impact of dry layers on rainfall. Rainfall in C is even further reduced.

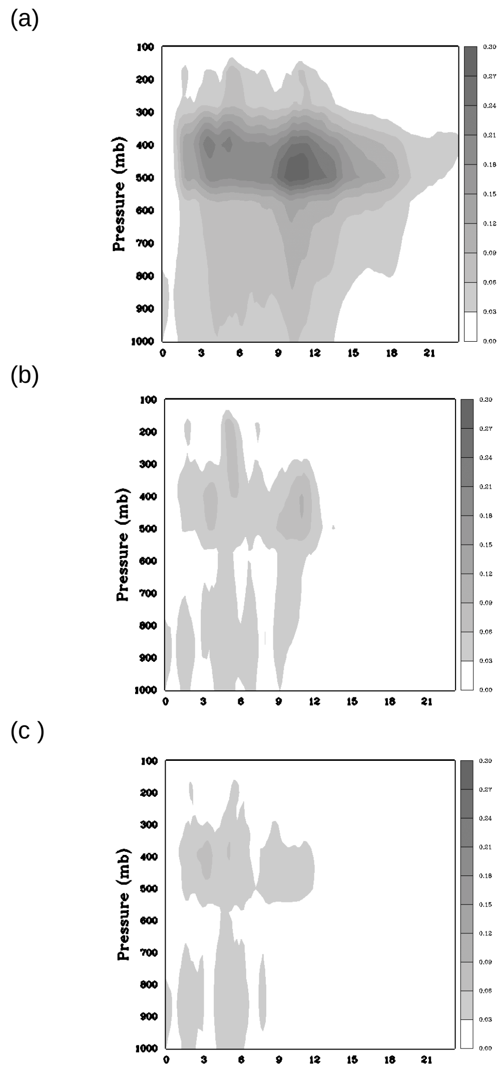


Figure 1. Mixing ratio (g/km) of precipitating hydrometeors averaged over the 3-km mesh grid. (a) Forecast A. (b) Forecast B. (c) Forecast C. The horizontal axis is forecast time in hours.

It is notable that about 40 percent of the rainfall reduction in B with respect to A can be attributed to a reduction in cloud base mass flux. This nonlocal impact of the upper-level dry layer on cloud base mass flux is not currently treated in some cumulus parameterizations such as the Emanuel (1991) scheme, in which the cloud base mass flux is determined by properties in the sub-cloud base layer. The present study supports the contention that the observed correlation between upper level moisture and precipitation in the tropical Pacific reflects to a significant extent the impact of entrainment of dry air on the development of precipitation. Alternatively, the observations could simply reflect the moistening of the environment by detrainment from deep convective clouds (Brown and Zhang 1997).

4. CONVECTIVE PARAMETERIZATION TESTS

The COAMPS experiments described in the preceding section provide a look at the sensitivity of deep convection to environmental moisture variability that may be helpful in assessing the performance of convective parameterizations. In order to utilize this information for the purpose of parameterization testing, data was output from COAMPS during the experiments that can be used to run COAMPS as a single column model (SCM) or semi-prognostic model (SPM). Data was output every 6 minutes, including large-scale advective tendencies, atmospheric profile data, radiative heating profiles, and surface fluxes. The advective tendencies are output for 21 overlapping domains of varing size as illustrated in Fig. 2.

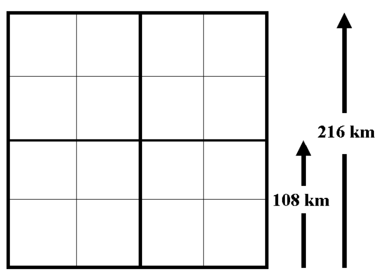


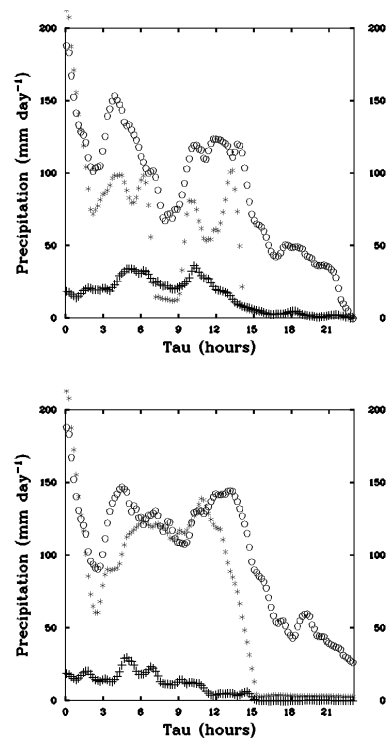
Figure 2. Subdivision of 3 km mesh grid into 21 boxes for SCM tests.

In this figure there are 16 square regions or boxes with sides of length 54 km. These boxes comprise the same region as 4 larger boxes with sides of length 108 km. In turn, these 4 larger boxes comprise the same region as a single box with sides of length 216 km. By running the SCM for each of these 21 boxes and averaging results for equal-sized boxes one obtains results showing the performance of a given convective scheme as it varies with grid dimension. This feature is significant because the performance of convective parameterizations can be expected to depend on the horizontal grid resolution. This is true for example of the Kain – Fritsch (1990) scheme which requires information on the local cloud environment, and hence is best suited for relatively high resolution grids (~ 35 km or less). Available observational datasets suitable for SCM testing generally represent fairly large regions, on the order of several hundred kilometers, and may not be suitable for testing of parameterizations for mesoscale models. The 54-km, 108-km and 216-km horizontal scales chosen for the current work could easily be modified in future studies.

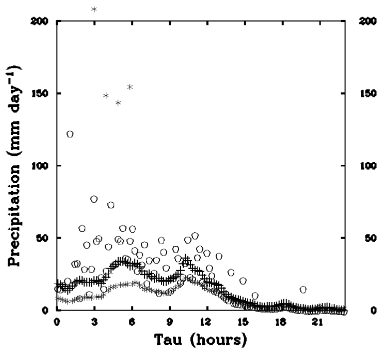
Semi-prognostic simulations were carried out using the data output from forecasts A and B of section 3. Simulations were performed using both the Emanuel convective parameterization and the Kain-Fritsch convective parameterization. Rainfall rates from these semi-prognostic tests are plotted in Fig. 3 as a function of forecast time. Results are shown for both the 54-km resolution (average of 16 boxes) and the 216-km resolution, as well as the results predicted explicitly without the aid of a convective parameterization on the 3-km mesh COAMPS grid. The results obtained from the convective parameterizations are somewhat mixed. The Emanuel scheme overpredicts the precipitation by a considerable amount. Whereas the amount of precipitation for forecasts A and B was 15.6 mm and 9.0 mm, respectively, the Emanuel scheme in the 216-km resolution SPM simulations gives corresponding values of 46mm and 69mm.

(a)

(b)



(c)



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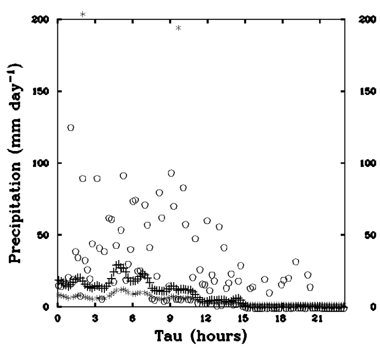


Figure 3. Rainfall rates: 3-km mesh COAMPS (+), 216 km SPM (*), 54 km SPM (o). (a) Forecast A with Emanuel SPM results. (b) Forecast B with Emanuel SPM results. (c) Forecast A with Kain-Fritsch SPM results. (d) Forecast B with Kain-Fritsch SPM results.

The predicted rainfall amounts from the 54-km resolution Emanuel SPM simulations were even higher. The rainfall totals are summarized in Table 1 for the semi-prognostic runs. Results are given in mm.

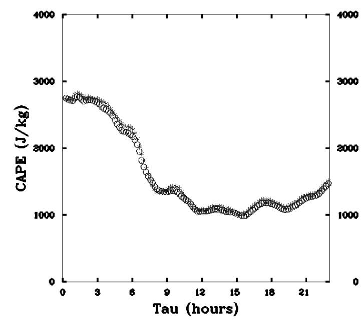
TABLE 1

Model	COAMPS 3-D		Emanuel SPM		Kain-Fritsch SPM	
Run	A	B	A	B	A	B
54 km	15.6	9.0	88.0	100.7	21.2	23.7
216 km	15.6	9.0	45.6	69.1	16.6	22.5

The Kain-Fritsch scheme appeared to do better in these tests than did the Emanuel scheme. It should be noted, however, that in the 216-km SPM run the rainfall was almost entirely due to large-scale condensation. The 54-km SPM runs with the Kain-Fritsch scheme, on the other hand, did produce a considerable amount of convective rainfall. The better performance of the Kain-Fritsch scheme at higher resolution here is indeed what one would expect. At higher resolution convergent circulations responsible for initiating the convection are better resolved. In addition, the convective parameterizations used here both employ a buoyancy sorting scheme to predict convective mass flux profiles that can be expected to be very sensitive to the local environmental profile. The poor performance of the Emanuel scheme here needs to be investigated further. However, a contributing cause appears to be the considerable sensitivity of the scheme to a parameter in the closure scheme used to compute the cloud base mass flux. This point is the subject of ongoing work.

Although the COAMPS 3-km mesh grid results show a decrease in precipitation for Forecast B (with the dry boundary conditions) with respect to Forecast A, this result is not duplicated in the SPM results shown in Table 1. It should be noted that although the experiment was designed to examine the impact of dry air above the source layer for the convection, the decrease in convection in Forecast B has the impact of maintaining a higher amount of convectively available potential energy (CAPE), as shown in Fig. 4.

(a)



(b)

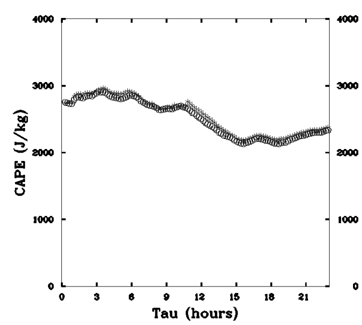


Figure 4. CAPE (J/kg) for (a) Forecast A and (b) Forecast B, as it varied with forecast time.

The convective parameterizations appear to be responding more to the greater amount of CAPE than to the inhibitory effect of the drier air in Forecast B. In order to further examine the response of the Kain-Fritsch scheme to moisture variations at upper levels, an additional test set of SPM runs was made for Forecast A. In these runs, the water vapor mixing ratio above 600mb was reduced by 70 percent. In this case, at 54-km resolution the rainfall was reduced by about 10 percent from the run with the unmodified sounding, but was still about 20 percent greater than that produced on the 3-km mesh COAMPS grid in Forecast A. More tests of this type are planned, including a look at the response of the Emanuel scheme to such changes.

The SPM tests ideally (given a perfect model) provide a picture of how the parameterizations would perform in the real atmosphere. In a forecast model, there is an adjustment of the atmospheric profile due in part to imperfection in the parameterized physics. Errors in the SPM tests are an indication that the model atmosphere will have an associated bias with respect to the real atmosphere. The bias can be investigated to some degree through SCM experiments. For the present work, SCM tests analogous to the SPM tests discussed above were carried out. Results for rainfall amount over the 24-hour forecasts are given in Table 2 in mm.

TABLE 2

Model	COAMPS 3-D		Emanuel SCM		Kain-Fritsch SCM	
Run	A	B	A	B	A	B
54 km	15.6	9.0	16.4	10.6	13.6	7.7
216 km	15.6	9.0	15.7	9.0	10.7	4.9

Note the considerably improved performance of the Emanuel scheme in the SCM tests compared to the SPM results in Table 1. The Kain-Fritsch scheme performs fairly well at 54-km, but the performance suffers considerably at the coarser resolution. A more indepth look at the performance of these schemes can be obtained by plotting the temperature and moisture biases as computed based on the COAMPS 3-km mesh grid data. This work is currently in progress.

5. DISCUSSION

The dry layer that was introduced into the quasi-cloud resolving scale COAMPS simulations had the effect of signficantly reducing the amount of convective rainfall. Approximately 40 percent of the rainfall reduction can be explained by an observed reduction in cloud base mass flux. Though further work is needed to better understand this nonlocal effect, the lack of a treatment for it in the Emanuel scheme may have contributed to its poor performance in the SPM tests reported here. Preliminary tests not shown here suggest that the 'temperature perturbation' parameter in the scheme's cloud base mass flux closure may also have contributed to the overprediction of rainfall in the current SPM tests. The Kain-Fritsch scheme employs a closure that accounts for cloud feedbacks on vertically integrated (through the depth of the cloud) parcel buoyancy, but it is not clear whether the observed sensitivity of cloud base mass flux in the COAMPS 3-km mesh grid noted here is adequately treated. Whatever its cause, the signficant overprediction of rainfall by the Kain-Fritsch scheme in the 54-km SPM tests reported here suggests that further work is needed to properly account for the sensitivity of convection to moisture variability aloft.

6. REFERENCES

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ACKNOWLEDGEMENTS

This research was sponsored by the Office of Naval Research, through the Naval Research Laboratory, Program Element 0601153N. The work was supported in part by a grant of computing time from the Department of Defence's High Performance Computing Program.