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A NUMERICAL STUDY OF CONVECTION IN EASTERLY WAVES USING THE "RELAX TO BALANCE" APPROXIMATION

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1. INTRODUCTION

An important but difficult problem in the study of atmospheric dynamics is the interaction of convection with the large-scale circulation. One example of this interaction is the interplay of convection with easterly waves. Easterly waves can influence convection by exerting a forcing on the system in the form of quasi-geostrophic lifting, surface fluxes, and advection of dry or moist air. In turn, convection can supply heat and moisture to potentially energize the passing easterly wave, resulting in a complex feedback effect. In spite of the observational insight into the structure and energetics of the easterly waves (Reed and Recker 1971; Cho and Ogura 1974; Reed, Norquist and Recker 1977; and Norquist, Recker and Reed 1977), little is known about this complex interaction.

The present investigation constitutes the first step in understanding the interplay between convection and easterly waves. In particular, we implement a cumulus ensemble model in the context of a "relax to balance" approximation, which is based on Sobel and Bretherton's (2000) weak temperature gradient approximation, to study the effects of quasi-geostrophic lifting on convection. The approximation, numerical experiment, and results are described below.

2. "RELAX TO BALANCE" APPROXIMATION

The relax to balance approximation is an extension of Sobel and Bretherton's (2000) weak temperature gradient approximation (WTG). The basic idea behind WTG is that the large-scale tropical dynamics will have a tendency to horizontally homogenize the vertical profile of virtual temperature. In the tropics, radiative cooling and surface heat fluxes produce buoyancy anomalies which locally alter the potential temperature profiles. Gravity waves redistribute these anomalies over a large domain, causing the local profiles to relax to the large scale mean. In the context of a cumulus ensemble model, this effect is achieved by generating a hypothetical mean vertical velocity that is just sufficient to counteract the effects of local convective and radiative heating. The resulting vertical advection greatly impacts the evolution of convection (Raymond and Zeng 2005).

The WTG idea of relaxation to horizontal homogeneity in the tropics is a special case of a more general principle of "relaxation to a balanced state." In general, the balanced state is not static, but varies slowly with time; thus, introducing a time-dependence in the reference profiles allows studies of the response of convection to various forcing mechanisms. In particular, the reference profiles can be adjusted to reflect quasi-geostrophic lifting that may result from a passing easterly wave.

3. QUASI-GEOSTROPHIC LIFTING IN EASTERLY WAVES

To investigate the response of convection to quasi-geostrophic lifting, we impose a lifting perturbation, δz, given by:

$$\delta z = \Delta z \left(\frac{z}{h}\right)^2 \mathrm{e}^{2(1-z/h)} \quad , \qquad (1)$$

where Δz is the maximum vertical displacement of an air parcel, z is the height of the parcel, and h is the location of the maximum vertical displacement (i.e., a parcel at height h is lifted by an amount Δz; parcels above and below h are lifted by a smaller amount, δz).

The lifting given by (1) alters the potential temperature profile according to

$$\delta\theta = -\frac{\partial\theta}{\partial z}\delta z \quad . \qquad (2)$$

A similar expression holds for perturbations in the mixing ratio profiles. The model is capable of independently perturbing the potential temperature and mixing ratio profiles.

In order to model the effects of quasi-geostrophic lifting that is consistent with a passing easterly wave, we imposed lifting perturbations (Δz) at two levels: one that corresponds to a cooling of about 0.5° C

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Experiments	$\delta\theta$	δr_t	$\delta\theta$ and δr_t
Δz_1 and Δz_2	5.5	2.9	4.5
Δz_1	6.8	3.6	7.7
Δz_2	-0.1	1.6	-1.1

Table 1: The change in rainfall (mm/day) for each trial. $\delta\theta$ and δr_t indicate whether potential temperature or moisture profiles were perturbed, resp.; Δz indicates the lifting perturbation: $\Delta z_1 = 100$ m at $h = 3$ km and $\Delta z_2 = -100$ m at $h =$10 km.

at a height (h) of 3 km, and a second that corresponds to a warming of about 0.5° C at $h = 10$ km. This is roughly consistent with the temperature structure observed by Reed and Recker (1971), and Reed, Norquist and Recker (1977).

4. RESULTS

Given the lifting prescribed in (1) of the previous section, we performed several numerical experiments and looked at the rainfall generated by the model as a proxy for convection. These experiments included both independent and simultaneous perturbations of potential temperature and moisture profiles. All experiments were run using a 2-dimensional model with a 256 km horizontal domain. The initial profiles for the experiments were obtained from a horizontal and time average of a previous simulation with a steady imposed horizontal surface wind of 7 m/s and an SST of 303 K. After the model ran for 10 days, the perturbation was imposed on the reference profile, and the change in rainfall was averaged over 5 days. Prior to the perturbation, the average rainfall was about 12 mm/day. The changes in rainfall after the perturbation for each experiment are summarized in Table 1.

The experiments that most represent a disturbance associated with a passing easterly wave consist of a quasi-geostrophic lifting at 3 km and a descent at 10 km (labeled as "Δz_1 and Δz_2" in Table 1). For this set of experiments, the largest increase in rainfall was about 5.5 mm/day which occured when the lifting only perturbed the potential temperature profile ($\delta\theta$). Perturbing only the moisture profile (δr_t) increased the rainfall by only 2.9 mm/day. This result is consistent with previous outcomes from this technique: perturbations in the temperature profile have a larger effect on convection than perturbations in moisture. Perturbing both temperature and moisture profiles increased the rainfall by about 4.5 mm/day. Though we might have expected this to produce the largest increase in convection, there may be overall nonlinearities in the combination of warming and drying at upper levels with the cooling and moistening at lower levels. To investigate this possibility further, we examined the effect of *either* a lifting at 3 km or a descent at 10 km.

The set of experiments that correspond only to a lifting (and hence a cooling or moistening) at low levels are represented by "Δz_1" in the table. In this case, all outcomes increased the amount of rain produced, with the cooling ($\delta\theta$) having a larger effect than moistening (δr_t); 6.8 mm/day vs. 3.6 mm/day, respectively. The combined effect of cooling and moistening produced the greatest increase in rain, 7.7 mm/day. Again we note that the combined effect is nonlinear, and is actually less than the sum of the results of independent temperature and moisture perturbations.

The third set of experiments corresponded to a descent at 10 km which resulted in either a warming or a drying of the atmosphere. In this case, perturbing the temperature has almost no impact on the precipitation, suggesting that the lower level perturbations are more significant than the upper level perturbations. The drying associated with the perturbation in moisture appears to have increased the rainfall. We are skeptical of this result and note that this probably falls within the error bars (roughly estimated to be about 2 mm/day), and thus should be taken with a grain of salt. The combined effect of drying and warming produced an overall decrease in the amount of rain (as expected, though again probably falls within the error bars).

5. CONCLUSIONS

The interplay of easterly waves and convection is complicated and not well understood. Using a cumulus ensemble model in the context of a "relax to balance" approximation, we have begun to investigate this particular interaction of convection with the larger atmospheric scales. As a first step, we have ignored any potential feedback effects that may result from the interaction, and have only considered the effect of quasi-geostrophic lifting on convection. The lifting was prescribed to be consistent with the observed structure of a passing easterly wave.

The numerical experiments that we have performed so far suggest that quasi-geostrophic lifting at lower levels has a bigger impact on convection than lifting at higher levels. Additionally, changes in the vertical profile of potential temperature seem to have a greater impact than changes in the moisture profile. This is the extent of we can presently conclude about the effect of quasi-geostrophic lifting on convection. Future studies should provide insight to the relative importance of quasi-geostrophic lifting with other forcing mechanisms.

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