P2.15 QUASI-EQUILIBRIUM CLOSURE IN CONVECTIVE PARAMETERIZATION: A REVISIT

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1. INTRODUCTION

Convective parameterization in global climate models (GCMs) represents the collective effect of convection within a GCM grid in terms of the resolvable scale quantities. It is one of the most difficult problems facing the GCM community in improving climate simulation and predictions. Within a convective parameterization, a closure empirically determining the relationship between convection and the resolved scale fields is required to close the system of equations. Most of the convective parameterization schemes nowadays use the quasi-equilibrium assumption proposed by Arakawa and Schubert (1974) for this purpose, which assumes that statistically the generation of convective instability by the resolvable scale processes is in quasi-equilibrium with the removal of convective instability by convection. Recently Zhang (2002) found that such a quasi-equilibrium assumption is not valid in the midlatitude continental convection environment. The main reason for it is the large contribution to the net change of convective available potential energy (CAPE) from the thermodynamic changes of the boundary layer air. This study extends the analysis to the tropical data sets. We will systematically examine the similarities and differences between tropical and midlatitude convection in this respect.

2. DATA AND ANALYSIS METHODS

The tropical data used in this study are from TOGA COARE intensive observation period. They represent the spatial average over the Intensive Flux Area at 6-hourly resolution for the entire 120 days observation period. The data were obtained from R. H. Johnson of Colorado State University and included the sounding moisture correction. The midlatitude data are from the summer 1997 intensive observation period at the Southern Great Plains (SGP) site of the Atmospheric Radiation Measurement (ARM) program. The observations cover 29 days from June 19 to July 18 1997. The data used to provide the necessary basic meteorological fields include upper-air soundings, wind fields from wind profilers, and the gridded meteorological fields from the NCEP Rapid Update Cycle analysis. They were processed by Zhang et al. [2001] using variational analysis to provide the large-scale forcing for single-column model studies in the ARM program. The soundings were available at 3-hr intervals. However, the objective analysis interpolates them to 20-min intervals and provide a single temperature and moisture profile at each time for the entire area representing a GCM grid point. The large-scale data at the 20-min interval resolution are used in this study to compute the needed fields, such as the time rate of change of CAPE. These fields are then averaged over each 3-hr period to obtain the final results. The vertical resolution of the data is 50 mb starting from 965 mb and ending at 115 mb.

CAPE in the atmosphere is defined as the vertical integral of buoyancy of a parcel lifted from the boundary layer following the moist adiabat to its neutral buoyancy level by:

$$A \equiv CAPE = \int_{p_t}^{p_b} R_d (T_{vp} - T_{ve}) d \ln p \ , \qquad (1)$$

where Tvp and Tve are the parcel's and its ambient virtual temperature, pb and pt are the pressure of the parcel's originating level and the neutral buoyancy level, respectively. According to Arakawa and Schubert (1974), CAPE change is due to two groups of processes: the convective processes and the large-scale processes (everything other than convective), that is,

$$\frac{\partial A}{\partial t} = \left(\frac{\partial A}{\partial t}\right)_{cu} + \left(\frac{\partial A}{\partial t}\right)_{ls} , \qquad (2)$$

where subscripts cu and ls stand for convective and large-scale processes. We can rewrite eq. (2) as

$$\left(\frac{\partial A}{\partial t}\right)_{cu} = -\left(\frac{\partial A}{\partial t}\right)_{ls} + \frac{\partial A}{\partial t} \qquad (3)$$

to diagnose the CAPE change due to convection from the observed net CAPE change and the CAPE change from the large-scale forcing. The AS quasi-equilibrium assumption requires that $\partial A/\partial t << \left(\partial A/\partial t\right)_{ls}$. If this assumption is valid, we expect the diagnosed CAPE change due to convection to be approximately balanced by the CAPE change due to the large-scale forcing.

Another way to look at the convective quasi-equilibrium issue is to follow the approach of Emanuel et al. (1994). From eq. (1), the time rate of change of CAPE is given by:

$$\frac{\partial A}{\partial t}=\frac{\partial}{\partial t}\left\{\int_{p_t}^{p_b} R_d(T_{vp}-T_{ve})d\ln p\right\}$$
$$=\int_{p_t}^{p_b} R_d\left(\frac{\partial T_{vp}}{\partial t}-\frac{\partial T_{ve}}{\partial t}\right)d\ln p-R_d(T_{vp}-T_{ve})_{p_t}\frac{\partial p_t}{\partial t}$$

The last term on the second line vanishes since the virtual temperature of the parcel at the neutral buoyancy level is the same as that of its environment. Thus, CAPE change consists of two parts, that due to the free tropospheric environmental virtual temperature change and that due to the parcel's (or boundary layer) virtual temperature change, that is,

$$\frac{\partial A}{\partial t}=\frac{\partial A_p}{\partial t}+\frac{\partial A_e}{\partial t}\,, \qquad (4)$$

where

$$\frac{\partial A_p}{\partial t}=R_d\int_{p_t}^{p_b}\frac{\partial T_{vp}}{\partial t}d\ln p$$
$$\frac{\partial A_e}{\partial t}=-R_d\int_{p_t}^{p_b}\frac{\partial T_{ve}}{\partial t}d\ln p$$

The quasi-equilibrium assumption requires that $\partial A/\partial t << \partial A_p/\partial t$ or $\partial A/\partial t << \partial A_e/\partial t$. Using the observational data, we can examine the validity of the quasi-equilibrium assumption in the tropics and midlatitudes.

3. RESULTS

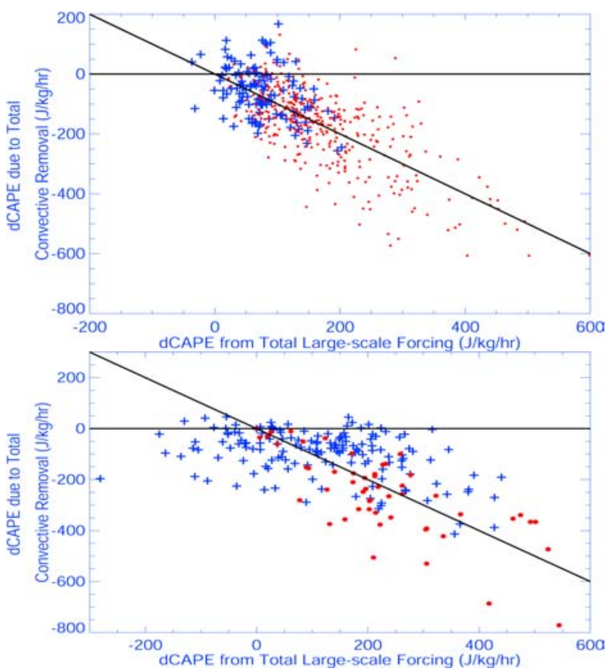

Fig. 1: Scatter plots demonstrating the validity of the Arakawa-Schubert quasi-equilibrium assumption in the tropics (top) and midlatitude (bottom) convection environment. Dots are for convective periods and crosses are for non-convective periods. The x-axis is the CAPE change due to the large-scale forcing, and the y-axis is the CAPE change due to convection diagnosed from eq. (3).

Fig. 1 shows the scatter plots of convective removal of CAPE diagnosed from eq. (3) versus the large-scale generation of CAPE for the 120-day TOGA COARE IOP (top) and the 29-day ARM SGP IOP (bottom). For the COARE IOP each point represents a 6-hr average, and for the ARM SGP IOP each point represents a 3-hr average. If the AS quasi-equilibrium is valid, points during convective periods should fall close to the diagonal line. It is seen that although they tend to fall in the right direction in general, there is a significant degree of scatter in both the tropics and the midlatitude. Based on this figure, it would be difficult to state that the AS quasi-equilibrium is a good approximation in either the tropics or the midlatitudes.

Similar conclusions can be made using the alternative analysis approach. Fig. 2 shows the scatter plots of the terms in eq. (4) for the ARM SGP site data. The top frame shows the scatter plot of the net CAPE change versus the CAPE change resulting from the parcel's temperature change. For a non-entraining parcel, its temperature is entirely determined by the boundary layer equivalent potential temperature at the parcel's originating level. The bottom frame shows the scatter plot of the CAPE change resulting from the ambient temperature versus the net CAPE change.

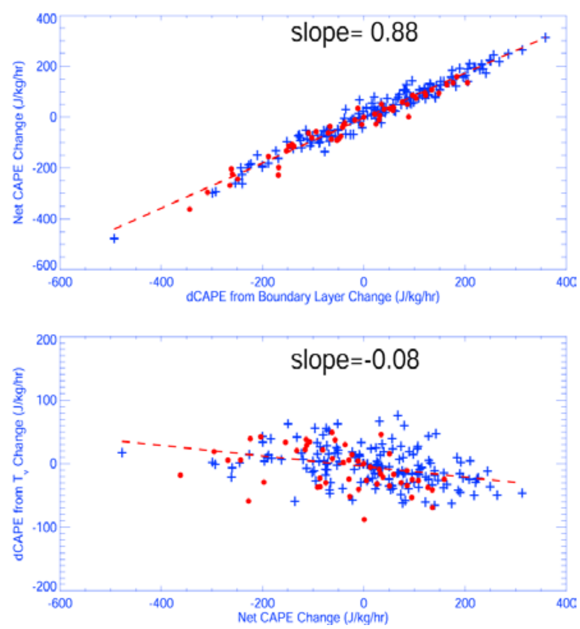

Fig. 2: Scatter plot of the net atmospheric CAPE change versus that due to the boundary layer temperature and moisture changes (top), and scatter plot of CAPE change due to parcel's ambient temperature change versus the net atmospheric CAPE change using data from the ARM SGP site. Dots are for convective periods and crosses are for non-convective periods.

Fig. 2 suggests that the CAPE variations resulting from changes in the boundary layer temperature and moisture are largely reflected (about 90%) in the net atmospheric CAPE variations, and that the CAPE variations due to the ambient temperature changes above the parcel's lifting level are insignificant compared to the net CAPE change. Clearly, the quasi-equilibrium requirement that $\partial A/\partial t << \partial A_p/\partial t$ is not satisfied by the observations in the midlatitudes. Instead, it is seen that $\partial A_e/\partial t \approx 0$ relative to the net atmospheric CAPE changes.

The same results are observed for tropical convection, as shown in Fig. 3 for the TOGA COARE period. The net CAPE change accounts for 94% of the CAPE contribution from the boundary layer property changes, while CAPE variation due to the ambient air temperature change is about 10% of the net CAPE change. Note that in midlatitude land area, temperature and moisture variations in the boundary layer are large, contributing to about ± 300 J/kg/hr CAPE change a lot of times (top of Fig. 2). On the other hand, in the tropical oceanic environment, variations in the boundary layer temperature and moisture are relatively small, contributing to about ± 150 J/kg/hr CAPE change to the net CAPE variation most of the time (Fig. 3). Despite the large difference in the magnitude of variations in the boundary layer properties between midlatitude and tropical convection, the non-quasi-equilibrium characteristics shown in Figs. 2 and 3 are the same, and are consistent with Fig. 1.

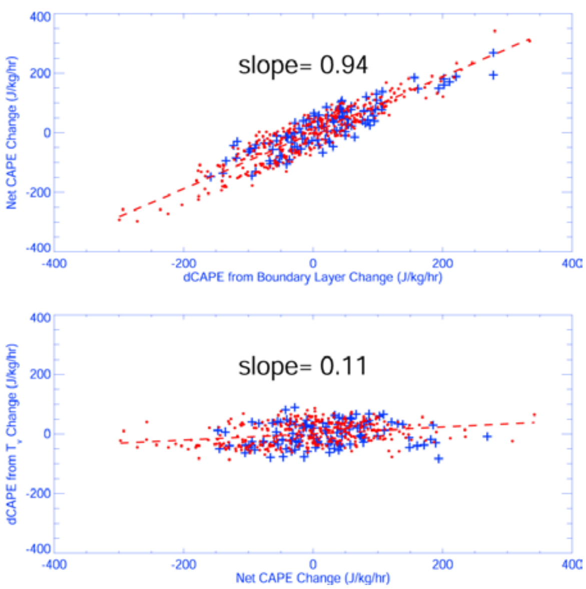

Fig. 3: Same as Fig. 2 except for the TOGA COARE period.

One important result from Figs. 2 and 3 is that $\partial A_e/\partial t \approx 0$. As the CAPE change due to contributions from the ambient air (or the free tropospheric air above the boundary layer) temperature change is a result of the large-scale and convective processes in analogy to eq. (2), we can write:

$$\frac{\partial A_e}{\partial t} = \left(\frac{\partial A_e}{\partial t}\right)_{cu} + \left(\frac{\partial A_e}{\partial t}\right)_{ls}$$

or

$$\left(\frac{\partial A_e}{\partial t}\right)_{cu} = -\left(\frac{\partial A_e}{\partial t}\right)_{ls} + \frac{\partial A_e}{\partial t} \qquad (5)$$

Eq. (5) is an alternative way to diagnose convection from the large-scale forcing and the observed changes of temperature and moisture. Note that in this approach only fields and large-scale forcing above the parcel's lifting level (or above the boundary layer) are involved. Fig. 4 shows the scatter plots of the diagnosed convective removal of CAPE due to changes of temperature in the free troposphere versus the large-scale forcing on the same fields. For a perfect relationship between convective removal and large-scale generation of CAPE from this partial contribution, the convective points should fall along the diagonal line, and the non-convective points should fall along the horizontal axis. For both the tropical convection (top) and the midlatitude convection (bottom), the agreement between the diagnosed and "predicted" convective removal of CAPE is excellent. Comparing with Fig. 1, it is clear that the improvement in predicting convection using the new approach is remarkable.

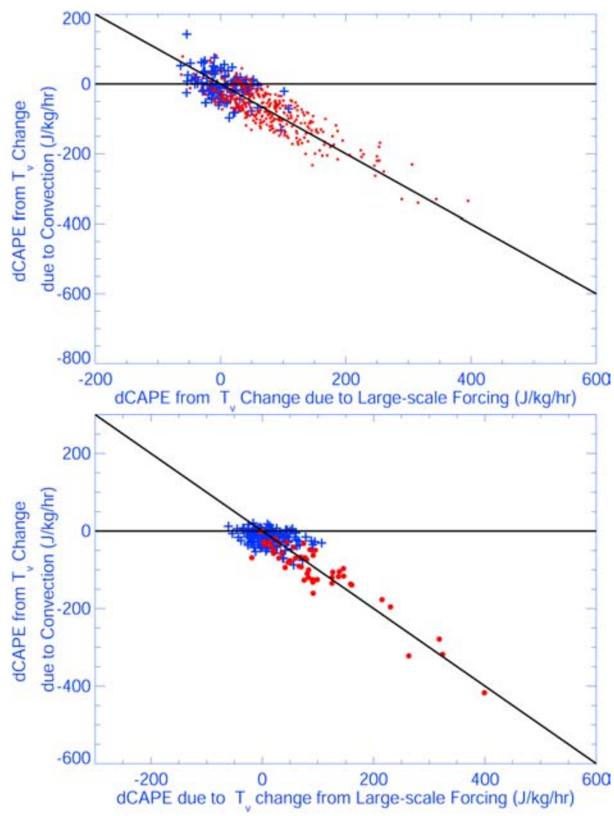

Fig. 4: Scatter plots of convective removal of partial CAPE contribution from the free tropospheric virtual temperature change versus its large-scale generation for the 120-day TOGA COARE period (top) and the 29-day ARM Southern Great Plains IOP (bottom). Dots are for convective periods and crosses are for non-convective periods.

4. SUMMARY

In this study, we used observational data from TOGA COARE and ARM Southern Great Plains site to examine the validity of the Arakawa-Schubert (1974) quasi-equilibrium assumption used in convective parameterization. It is shown that in neither tropical nor midlatitude convection environment, the AS quasi-equilibrium is an accurate description of the relationship between convective removal and large-scale generation of convective available potential energy in the atmosphere. This was further demonstrated using the approach first proposed by Emanuel et al. (1994). On the other hand, we showed that the contribution to the observed CAPE variation from the free tropospheric virtual temperature changes is negligible. This implies that the vertical integral over the convective layer of the virtual temperature change due to large-scale forcing is accurately balanced by convection. The results in Fig. 4 lend a strong support to this conclusion. Thus, we can and should incorporate this newly identified relationship between convection and the large-scale forcing into convective parameterization.

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5. REFERENCES:

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