Improving Convective Parameterization Using ARM Data

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Introduction

Convective parameterization is one of the most challenging issues in global climate models (GCMs). Convection, as represented by convective parameterization schemes in GCMs, is controlled by the large-scale dynamic and thermodynamic fields through a closure condition. Such a closure condition is typically determined empirically by the observed relationships between convective activity and the large-scale atmospheric states or processes. Arakawa and Schubert (1974) introduced the concept of quasi-equilibrium between convection and the large-scale forcing. The essence of the quasi-equilibrium assumption is that convection is controlled by the large-scale forcing in a statistical sense, in such a way that the stabilization of the atmosphere by convection is in quasi-equilibrium with the destabilization by the large-scale forcing.

While use of the quasi-equilibrium assumption in the tropics is justified by a number of observational and numerical studies (Arakawa and Schubert 1974; Arakawa and Chen 1987; Xu and Arakawa 1992; Xu and Randall 1998), few studies have systematically examined its performance in mid-latitude continental convection. In this study, we examine the Arakawa-Schubert convective quasi-equilibrium (hereafter referred to as the AS quasi-equilibrium) in mid-latitude continental environment. Based on the results, a modification to the AS quasi-equilibrium is suggested. We will test the modified quasi-equilibrium assumption using the Zhang and McFarlane (1995) convection scheme together with the National Center for Atmospheric Research (NCAR) CCM3 single column model (SCM).

Data and Analysis Approach

The data used in this study are from the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site during two intensive operational periods (IOPs) in the summers of 1995 and 1997. The summer 1995 IOP covers 16 days from July 18 to August 3, 1995, and the summer 1997 IOP covers 29 days from June 19 to July 18, 1997. The data was processed by Zhang et al. (2001) using variational analysis to provide the large-scale forcing for the SCM intercomparison projects to test convective parameterization schemes (Xie et al. 2001). The large-scale data at the 20-min interval resolution from their analysis are used in this study to compute the needed fields, such as the time rate of change of convective available potential energy (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.

In this study we use CAPE to measure convective instability in the atmosphere. CAPE is defined by:

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

Where $T_{vp} = T_p\,(1+0.608\,q_p - q_l)$ and $T_{ve} = T_e\,(1+0.608 q_e)$ are the virtual temperatures of the air parcel and its environment as it is lifted from its originating level p_b to the neutral buoyancy level p_t. R_d is the gas constant for dry air; q_l is the liquid water condensed as the air is lifted. T_e and q_e are the environmental or large-scale temperature and moisture, respectively. T_p and q_p are the parcel's temperature and moisture following a reversible moist adiabat. For non-entraining parcels, they are entirely determined by the temperature and moisture content at its originating level, which is assumed to be in the boundary layer (BL).

The time rate of change of CAPE is given by:

$$\begin{aligned}\frac{\partial A}{\partial t} &= \frac{\partial}{\partial t}\left\{\int_{p_t}^{p_b} R_d (T_{vp} - T_{ve}) d\,ln\,p\right\} \\ &= \int_{p_t}^{p_b} R_d \left(\frac{\partial T_{vp}}{\partial t} - \frac{\partial T_{ve}}{\partial t}\right) d\,ln\,p - R_d (T_{vp} - T_{ve})_{p=pt} \frac{\partial p_t}{\partial t}\end{aligned} \tag{2}$$

By definition, at the neutral buoyancy level $T_{vp} = T_{ve}$, thus the last term vanishes.

Using the convention of Arakawa and Schubert (1974), the net CAPE change can be written as the sum of that due to convective processes and that due to the large-scale processes:

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

The quasi-equilibrium assumption requires $\partial A/\partial t << (\partial A/\partial t)_{ls}$. Alternatively, noting that CAPE change can be expressed in terms of the changes in the parcel's and its ambient virtual temperature, Eq. (3) can also be rewritten as:

$$\frac{\partial A}{\partial t} = \frac{\partial A_p}{\partial t} + \frac{\partial A_e}{\partial t}, \tag{4}$$

where

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

represent CAPE changes resulting from the parcel's and its ambient virtual temperature changes, respectively. Thus, the quasi-equilibrium assumption requires $\partial A/\partial t << \partial A_p/\partial t$ or $\partial A/\partial t << \partial A_e/\partial t$.

Using the data, we compute $\partial A/\partial t$ and $(\partial A/\partial t)_{ls}$ as well as their decomposition into the parcel's and the environment's contributions. $(\partial A/\partial t)_{ls}$ is estimated using the observed large-scale advection, the radiative cooling from the European Centre for Medium-Range Weather Forecasts analysis, and the observed surface sensible and latent heat fluxes. The CAPE change due to the large-scale forcing is computed as the CAPE difference before and after the forcing is applied. To estimate the effect of surface turbulent fluxes on CAPE change, we assume the BL is well mixed and the surface fluxes are uniformly distributed over a layer near the surface. Since the BL depth is not known, different values (100 mb and 150 mb) for the layer depth over which surface fluxes are distributed are used for sensitivity tests. For the convenience of presentation, we will use the shorthand dCAPE for CAPE change, a subscript cu or ls for CAPE change resulting from convective or large-scale processes, and a superscript p or e for CAPE changes due to the parcel's or the environment's virtual temperature change.

Examination of Convective Quasi-Equilibrium

Figure 1 shows the scatter plots of the net CAPE change versus (vs.) the large-scale CAPE change with or without the surface flux forcing. The sloping solid line shows the 1:1 ratio for reference. During convective periods, when the large-scale forcing is large, dCAPE is slightly smaller in magnitude but opposite in sign; when the large-scale forcing is small, so is dCAPE. On the other hand, during non-convective periods, dCAPE is frequently much larger than that from the large-scale forcing. When the surface flux forcing is included, the CAPE change due to the total large-scale forcing is considerably larger. For fluxes distributed over a 100 or 150 mb layer, the qualitative characters are similar. For the quasi-equilibrium assumption to hold, all the points should fall near the x-axis. However, the figure shows that under convective situation dCAPE is only modestly smaller than $dCAPE_{ls}$ in magnitude. Under non-convective situations, most of the points fall along the 1:1 reference line. Clearly, in these cases the net CAPE change dCAPE is too large for the quasi-equilibrium between convection and the large-scale forcing to hold.

Another way of examining the quasi-equilibrium assumption is to determine if dCAPE << $dCAPE^p$. Figure 2 shows the time series and the scatter plot of the net CAPE change and the CAPE change due to changes in the BL temperature and moisture, i.e., dCAPE and $dCAPE^p$. In addition, it also shows the scatter plot between the net CAPE change and the CAPE change due to the free tropospheric virtual temperature change (dCAPE and $dCAPE^e$). Obviously, dCAPE is very close to $dCAPE^p$ at all times. The scatter plot of dCAPE vs. $dCAPE^p$ shows that under both convective and non-convective situations there is a high degree of correlation between the two, with a slope of 0.86. These suggest most of the net CAPE change results from the BL temperature and moisture changes. On the other hand, the CAPE change due to the free tropospheric virtual temperature changes is negligible compared to the net CAPE change, i.e. $dCAPE^e$ << dCAPE (bottom frame of Figure 2, with a linear regression slope of

-0.10). Recall the quasi-equilibrium assumption requires that dCAPE << dCAPE^p or dCAPE << dCAPE^e. Consistent with Figure 1, Figure 2 also shows the quasi-equilibrium assumption is not suitable in mid-latitude continental convective environment.

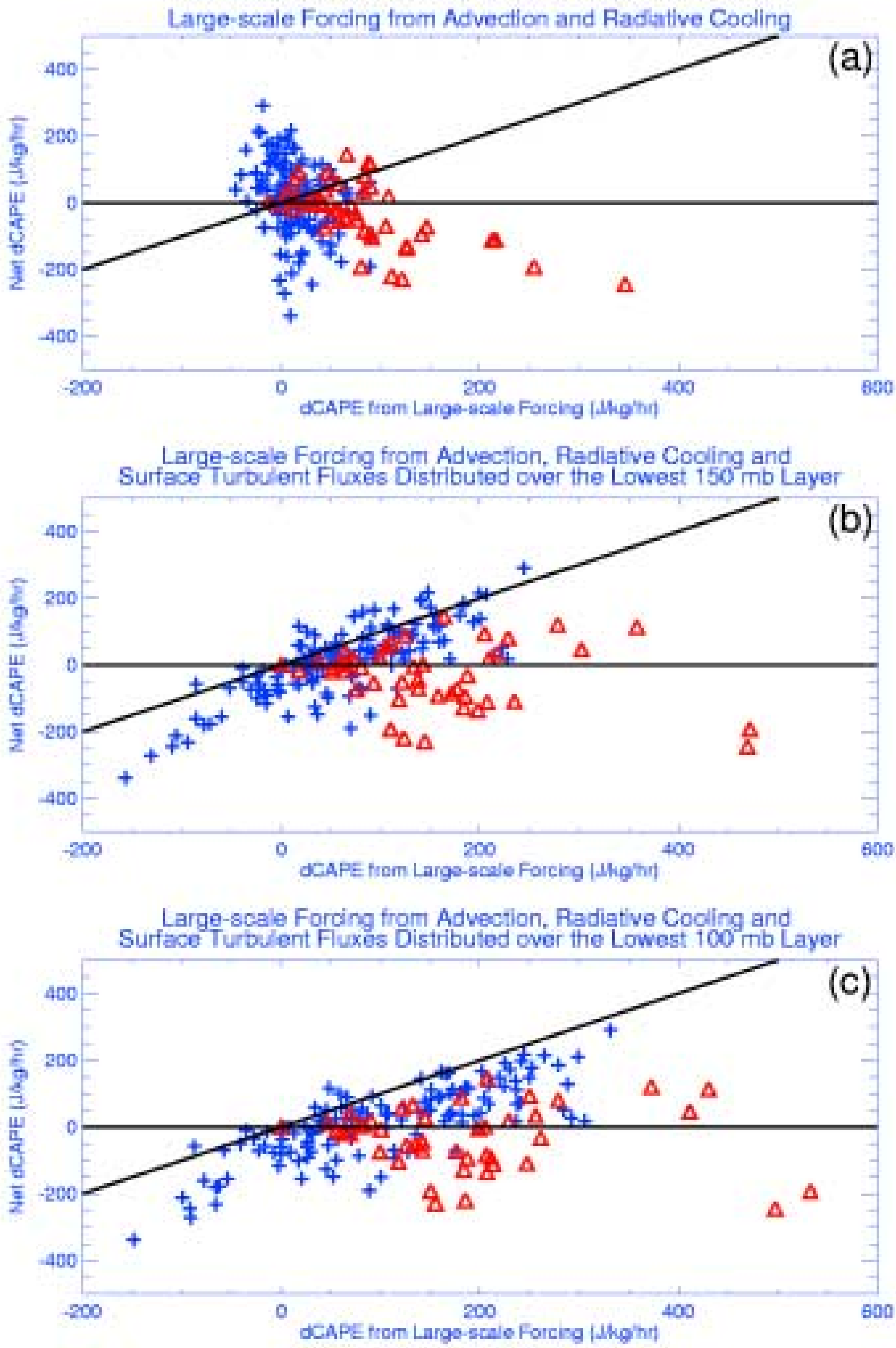

Figure 1. Scatter plots of the net CAPE change vs. the large-scale forcing (a) without surface fluxes, (b) with surface fluxes distributed over the lowest 150 mb layer, and (c) with surface fluxes distributed over the lowest 100 mb layer. Triangles and pluses are for convective and non-convective periods, respectively.

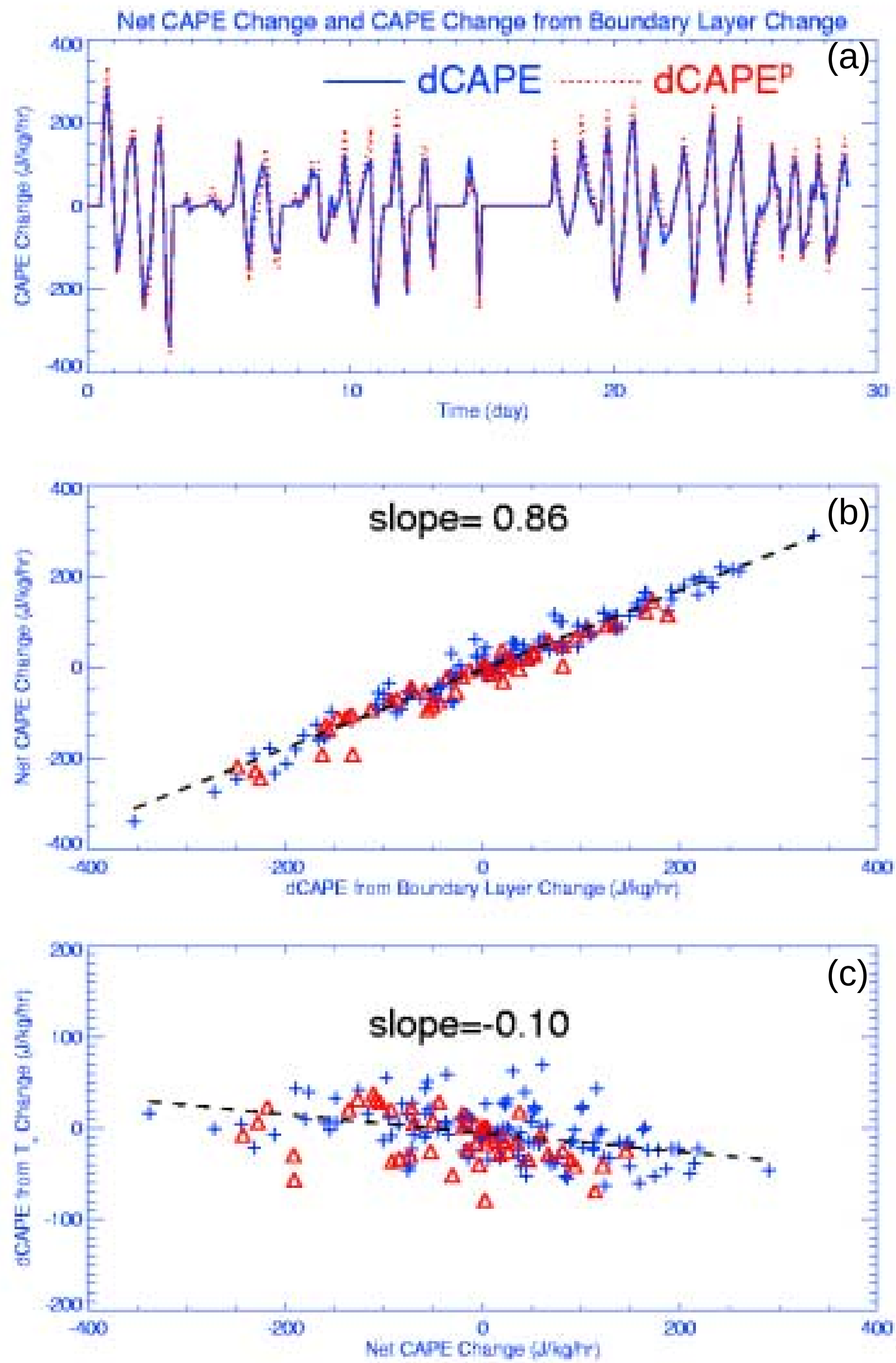

Figure 2. (a) Time series and (b) scatter plot of the net CAPE change and the CAPE change due to parcel's virtual temperature change, (c) scatter plot of CAPE change due to the ambient virtual temperature change vs. the net CAPE change. In (b) and (c) triangles and pluses are for convective and non-convective periods, respectively.

From the above analysis, it is reasonable to assume the CAPE change resulting from the free tropospheric virtual temperature changes is negligible, that is, $dCAPE^e \approx 0$. This is in contrast to the AS quasi-equilibrium. From the CAPE change point of view, the AS quasi-equilibrium assumes the CAPE change resulting from the boundary layer thermodynamic changes and that resulting from the free tropospheric virtual temperature changes are in balance, so the net CAPE change is negligible. On the other hand, here we suggest the CAPE change resulting from the boundary layer thermodynamic changes and the net CAPE change are in balance, and the CAPE change resulting from the free tropospheric virtual temperature changes is negligible.

This modification to the AS quasi-equilibrium is tested using observations from the summer 1995 IOP. Figure 3 shows the scatter plots of the net CAPE change attributable to the free tropospheric temperature and moisture changes vs. its large-scale contribution, i.e., $dCAPE^e$ vs. $dCAPE^e_{ls}$ and the total CAPE change vs. its large-scale contribution, i.e., dCAPE vs. $dCAPE_{ls}$ for the summer 1995 IOP. The top frame demonstrates the modified quasi-equilibrium works very well, that is, $dCAPE^e << dCAPE^e_{ls}$. The bottom frame is for the AS quasi-equilibrium assumption. Similar to Figure 1 (bottom), it shows that for convective periods, the net CAPE change is somewhat smaller in magnitude than that due to the large-scale forcing. For non-convective periods, the two are comparable, with most of the observations falling along the 1:1 line. Comparison of the two plots shows the modified quasi-equilibrium gives a more accurate description of the relationship between convection and the large-scale forcing.

Test of the Modified Quasi-Equilibrium in Convective Parameterization Scheme

Similar to the original AS quasi-equilibrium assumption, the modified one can also be used in the closure condition for convective parameterization schemes. Here we use the Zhang-McFarlane convection scheme and the CCM3 SCM to test the assumption proposed in the last section. The modified closure can be written as:

$$\int_{p_t}^{p_b} \left(\frac{\partial T_{ve}}{\partial t} \right)_{cu} d\,ln\,p = \max\{-\int_{p_t}^{p_b} \left(\frac{\partial T_{ve}}{\partial t} \right)_{ls} d\,ln\,p, 0\}$$

Since the temperature change in the convective layer due to convection is proportional to the cloud base mass flux, we have:

$$M_b = \frac{1}{k} \max\{-\int_{p_t}^{p_b} \left(\frac{\partial T_{ve}}{\partial t} \right)_{ls} d\,ln\,p, 0\} \tag{5}$$

where k is the vertically-integrated convective heating rate in the cloud layer per unit cloud base mass flux. Eq. (5) constitutes the new closure.

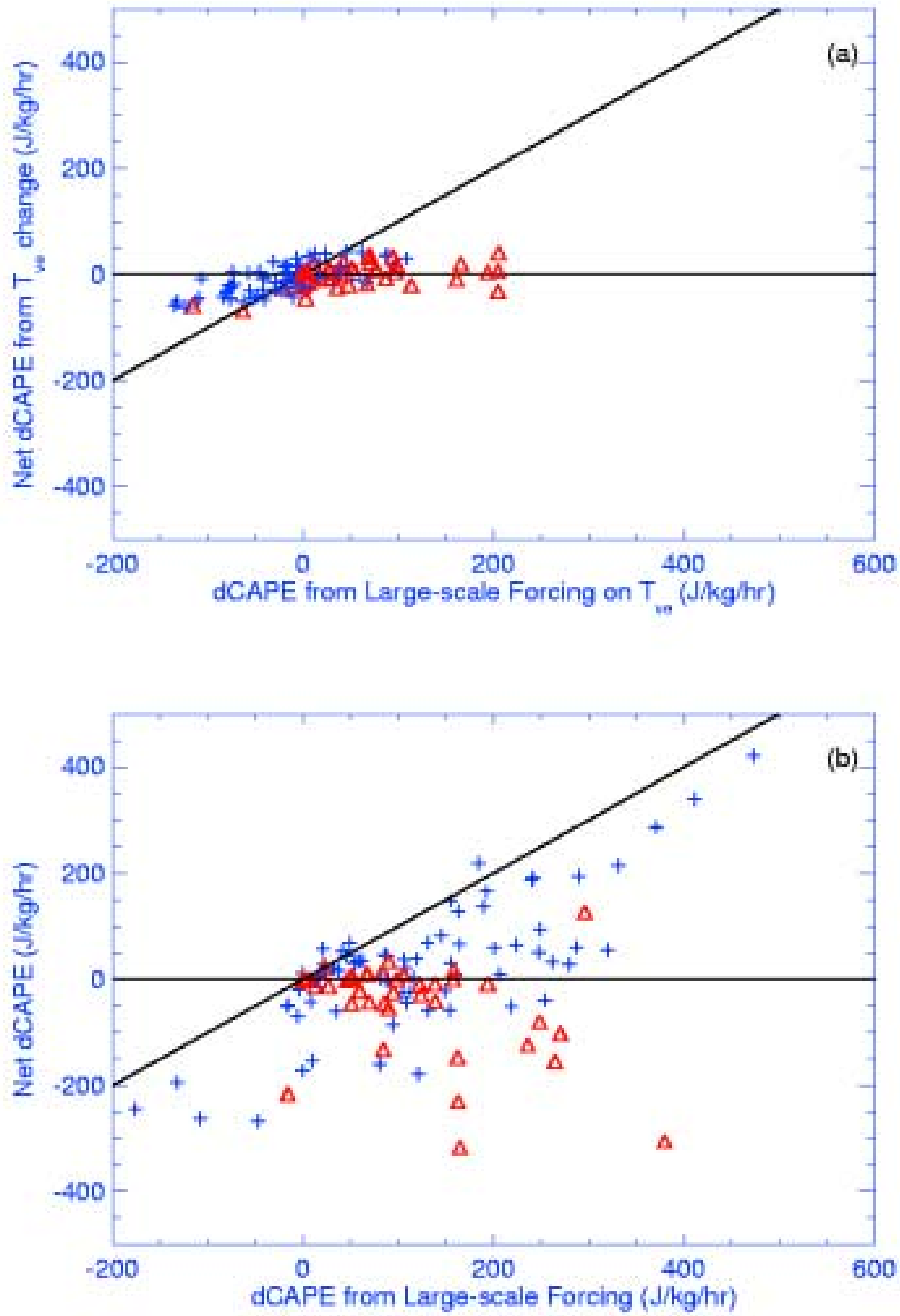

Figure 3. Scatter plots of (a) the CAPE change from the ambient virtual temperature change vs. the CAPE change from the large-scale forcing from advection and radiative cooling, (b) the net CAPE change vs. the CAPE change from the large-scale forcing including surface fluxes. (a) Shows the modified quasi-equilibrium, while (b) shows the AS quasi-equilibrium. Triangles and pluses are for convective and non-convective periods, respectively.

We use the large-scale forcing data for the summer 1997 IOP to drive the NCAR CCM3 SCM. Figure 4 shows the time-height cross section of the temperature biases for the simulations with the original and the new closure for the three convective periods selected by the convective parameterization intercomparison project (Xie et al. 2001) of the Cloud Parameterization and Modeling Working Group. For all three periods, the simulations with the original closure show large warm bias, in the range of 5 to 10 K, relative to the observed temperature fields. The warm biases start to develop early on during each period, and persist throughout the periods. The simulations with the new closure show significantly less temperature bias, most of the time less than 2.5 K in magnitude. In general, there is a slight cold bias in the mid-troposphere. The moisture bias field (not shown) suggests similar degree of improvement using the new closure.

Conclusions

This study analyzed the temperature and moisture data from the summers of 1995 and 1997 IOPs for summertime mid-latitude continental convection. It is shown that the net CAPE change, instead of being negligible as required by the AS quasi-equilibrium, is a major portion (90 percent of the CAPE change associated with changes in the BL thermodynamic properties. The contribution to the net CAPE change from the tropospheric temperature and moisture changes is insignificant (10 percent or less) compared to the net CAPE change. Based on this, we proposed a modified quasi-equilibrium between convection and the large-scale forcing. In physical terms, the essence of this modified quasi-equilibrium assumption is the mean virtual temperature changes in the free troposphere due to convection and the large-scale processes are in quasi-equilibrium, such that its net change is insignificant compared to the BL equivalent potential temperature change. This is in contrast to the AS quasi-equilibrium assumption that the mean tropospheric virtual temperature and the BL equivalent potential temperature change in concert.

We modified the closure condition of the Zhang and McFarlane convection scheme based on the new quasi-equilibrium assumption, and tested it using the SCM version of CCM3 for the summer 1997 IOP. The temperature and moisture biases in the simulations are significantly reduced compared to the simulations using the original closure.

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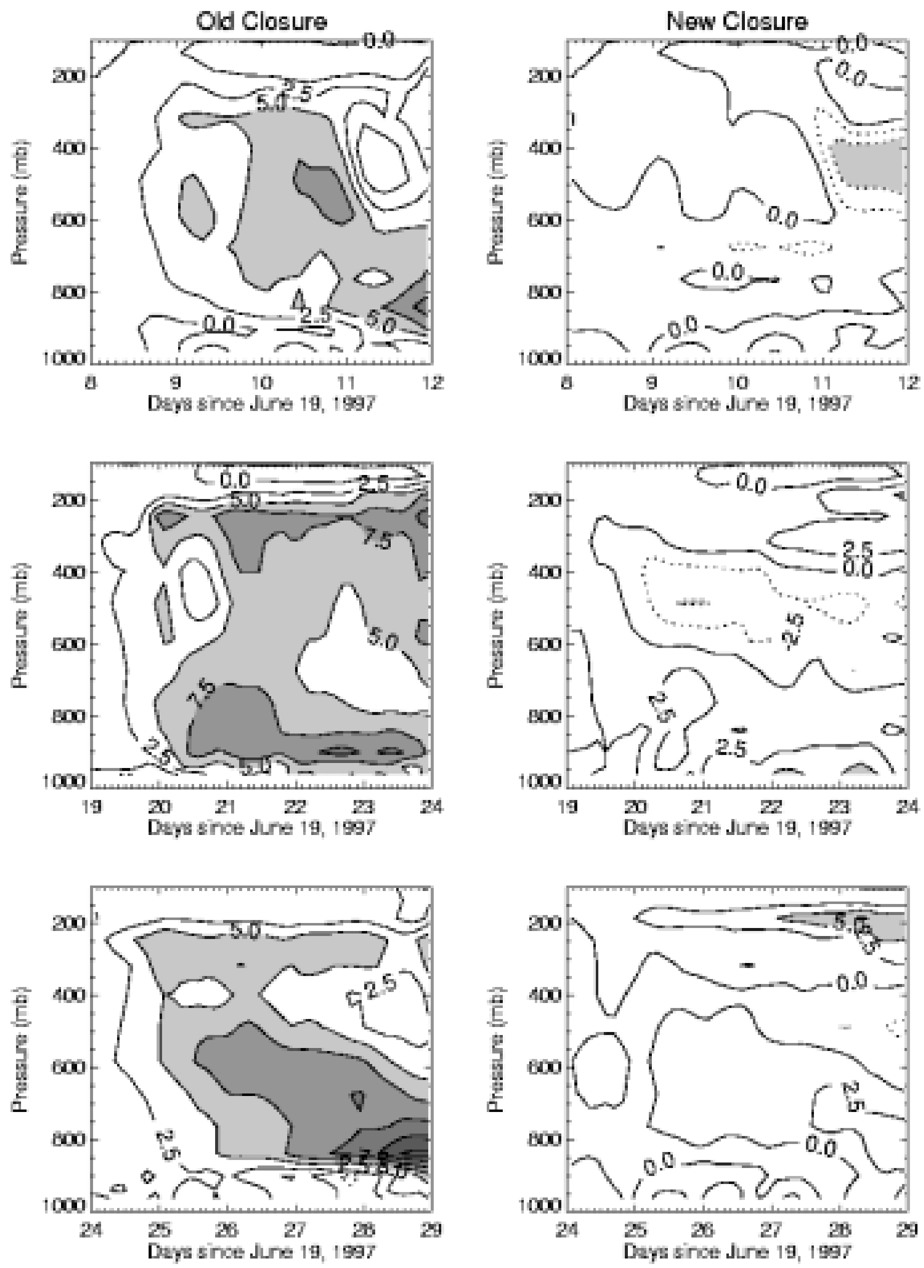

Figure 4. Time-height cross-section of temperature bias (model-observation) for three convectively active periods. The left panel is with the old closure and the right panel is with the new closure.

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