Evaluating Convection Parameterization Assumptions Using TWP-ICE Data

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INTRODUCTION

Convection parameterization schemes involve many assumptions, from convection closure and trigger, to simplified 1-D cloud models that determine in-cloud updraft and downdraft properties. The convection closure and trigger assumptions determine whether and how much convection occurs given the atmospheric conditions and the assumptions involved in building 1-D cloud models determine the vertical profiles of convective cloud physical properties. Both affect the feedback of convection to the large-scale atmospheric states. Consequently, GCM simulations of the global climate are very sensitive to these assumptions. This study evaluates several assumptions in the Zhang-McFarlane convection scheme. Specifically, for the closure assumptions, we evaluate the original CAPE-based closure, the free tropospheric quasi-equilibrium closure and a recently proposed dilute CAPE modification that is being considered by the NCAR Atmospheric Model Working Group (AMWG). For cloud model, we evaluate the conversion from cloud water to rain by comparing cloud ice in convective clouds to TWP-ICE observations and cloud-resolving model simulation. While our purpose is to improve treatment of convection in the NCAR CAM3, the work has general appeal to other GCMs as well, because these assumptions are used in one way or another by most GCMs. We will rely on the TWP-ICE single column model forcing data, together with other relevant datasets, such as the cloud-resolving model simulation, satellite and radar observations.

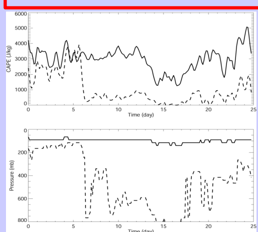

Fig. 1: Time series of undiluted CAPE (solid line) and dilute CAPE (dashed line) and corresponding zero buoyancy level as potential convection top. The dilute CAPE is multiplied by 5 to be plotted on the same scale.

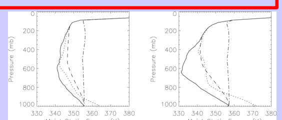

Fig. 2: Moist static energy (divided by C_p) and its saturation values (dotted) from two observations (day 4 on the left and day 24 on the right). The parcel's values with dilution (dashed) and without (dash-dotted) are also shown to demonstrate the effect of entrainment and moisture.

Data and Analysis

➤The sounding data for closure analysis in this work are from the TWP-ICE IOP, provided by the Cloud Modeling Working Group (Shaocheng Xie).

The analysis approach follows Zhang (2002, JGR). We calculate CAPE and its components and relate them to convection and large-scale forcing to determine which component gives the optimum description of the relationship between convection and the large-scale processes. In the calculations, the dilution effect of entrainment on CAPE is considered by entraining the environmental air at a rate such that the parcel's mass increases linearly with height at 1/km (relative to the cloud base value). CAPE is defined as:

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

where T_{vp} and T_{ve} are the parcel's and its environment's virtual temperature. The parcel's temperature calculation includes entrainment effects.

Three closure assumptions are tested: CAPE-based, conventional quasi-equilibrium and free-tropospheric quasi-equilibrium.

$$\left(\frac{dCAPE}{dt}\right)_{cu} = -\frac{CAPE}{t}$$

$$\frac{dCAPE}{dt} = \left(\frac{dCAPE}{dt}\right)_{cu} + \left(\frac{dCAPE}{dt}\right)_{ls} \approx 0$$

$$\frac{dCAPE_{env}}{dt} = \left(\frac{dCAPE_{env}}{dt}\right)_{cu} + \left(\frac{dCAPE_{env}}{dt}\right)_{ls} \approx 0$$

➤The C-Pol rainfall data and the satellite observations of cloud ice from other ARM PIs are used to estimate the cloud ice water content in convective clouds and to compare with single column model output.

To this end, the C-Pol convective rainfall is used to mask the convection regions. The satellite observations of cloud ice are provided by Guosheng Liu as a PI product. Each satellite footprint at the TWP-ICE IOP site (at ~16 km resolution) is collocated with the C-Pol convection masks (at 2 km resolution). A satellite pixel is considered convective if at least 70% of its area is under C-Pol's convection mask. The ice water content profiles from these identified grid points are averaged to obtain the convective cloud ice water distribution. The NCAR SCAM single column model is run to obtain the SCM model output. The Goddard CRM output from Tao for the TWP-ICE simulation is used to estimate cloud ice in convective cores (convective cores are identified by requiring vertical velocity > 3 m/s). These cloud ice water content profiles are compared to assess the realism of the convection parameterization.

RESULTS

➤Entrainment of environmental air has a dramatic effect on CAPE and the altitude of the convection top (Fig. 1), and this effect highly depends on the humidity of the environmental air. (Figs. 2 and 3).

➤When entrainment dilution is not considered, convection is better related to the free tropospheric forcing on CAPE than either CAPE itself or the total forcing on CAPE (Fig. 4). In terms of convection closure, CAPE is poorly related to CAPE removal by convection (Fig. 5), with a correlation coefficient of 0.2.

➤When entrainment dilution is included, convection is slightly better related to the dilute CAPE. The relationship between convection and the total large-scale forcing on CAPE is also improved. However, the relationship between convection and the free tropospheric large-scale forcing is degraded (Fig. 6).

➤In terms of convection closure, while the correlation between convective removal of CAPE and CAPE itself (i.e. CAPE-based closure) is improved significantly (0.57 for dilute CAPE vs. 0.2 for undiluted CAPE), both the free tropospheric quasi-equilibrium closure and that including the boundary layer forcing (i.e. the conventional quasi-equilibrium closure) work much better (Fig. 7).

➤The reason for comparable performance between free tropospheric and conventional quasi-equilibrium closures is that with strong entrainment dilution, the boundary layer influence on CAPE and its changes is diminished markedly, so that the contribution from boundary layer T and q fluctuations is only about 20% to the total large-scale CAPE change as compared to 2/3 in the undiluted CAPE case (Fig. 8).

➤Both TWP-ICE observations and CRM simulation indicate that cloud ice water content in convective cores is on the order of 0.3 g/m^3, with peak near 8 km in the observations and 10.5 km in CRM. The ice water content in SCAM simulation is a factor of 4 too small, with a peak near 9 km (Fig. 9).

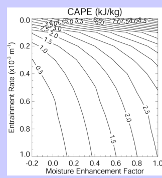

Fig. 3: CAPE as functions of entrainment and moisture based on the sounding on the right in Fig. 2. The varying moisture factor (x-axis) is achieved by keeping T fixed to the observed profile while q varying according to

where $f_q = \frac{q_m - q}{q_s - q}$, q is observed, q_s its saturation value and q_m modified value.

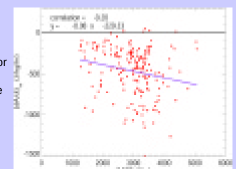

Fig. 5: CAPE change due to convection as function of CAPE to demonstrate the CAPE-based closure for undiluted CAPE calculation.

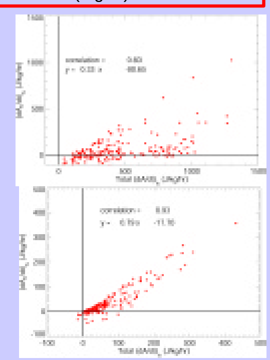

Fig. 8: Free tropospheric large-scale CAPE change as functions of total large-scale CAPE change for undiluted (top) and dilute CAPE (bottom).

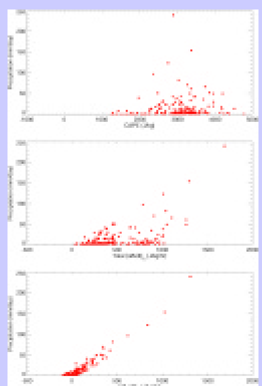

Fig. 4: Relationships between precipitation and CAPE (top), total large-scale CAPE change (middle), and free tropospheric large-scale CAPE change (bottom) for undiluted CAPE.

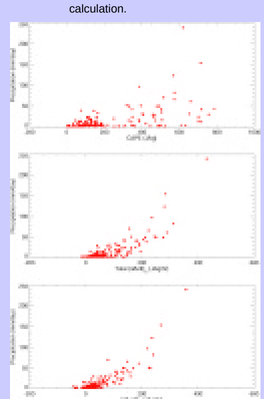

Fig. 6: Same as Fig. 4, but for dilute CAPE calculation.

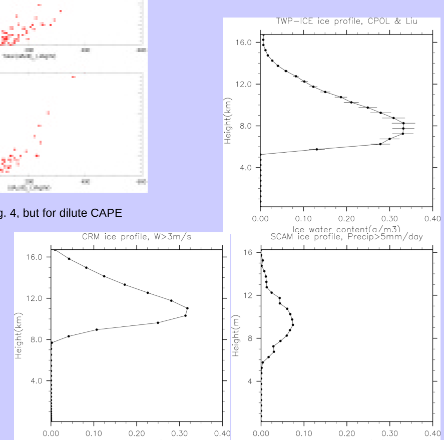

Fig. 9: Ice water content inside convective cores from observations (top), cloud-resolving model simulation (bottom left) and SCAM single column model (bottom right) for the TWP-ICE IOP.

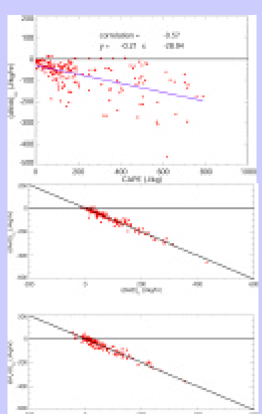

Fig. 7: Test of convection closure using dilute CAPE: CAPE-based (top), conventional quasi-equilibrium (middle) and free tropospheric quasi-equilibrium (bottom). For the quasi-equilibrium closures, x-axis is large-scale CAPE change with and without PBL forcing, and y-axis is the convective CAPE change with and without considering the PBL response, respectively.

CONCLUSIONS:

➤Undiluted CAPE is poorly correlated with convection.

➤Dilute CAPE correlates with convection modestly, with a correlation coefficient of 0.5 to 0.6 and implied relaxation time of 3 to 5 hours.

➤ With both undiluted and diluted CAPE, free tropospheric quasi-equilibrium works well (with correlation coefficients > 0.9). With dilute CAPE, including PBL forcing also works well.

➤There is too little cloud ice water in convection parameterization, maybe the conversion coefficient needs to be tuned down, or a more sophisticated cloud microphysics parameterization is needed for convection.

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