Closures for Cumulus Parameterizations- How Equilibrated is Deep Convection?

Leo Donner and Vaughan Phillips

GFDL/NOAA, Princeton University

I. A critical element of cumulus parameterizations is their *closure*, which relates overall cumulus intensity to properties of the resolved flow in the model, *e.g.,* cumulus mass flux to convective available potential energy (CAPE) or its generalization, cloud work function (CWF).

II. Despite the importance of closure, very little observational research until recently on the realism of hypothesized closures, which have been based on CAPE or CWF.

III. Typically, closures relate mass flux to CAPE or CWF by assuming (1) mass flux function of CAPE or CWF, (2) CAPE or CWF in quasi-equilibrium, (3) CWF evolves prognostically.

IV. Zhang (2002, *JGR*) recently used ARM observations to examine III(1) and III(2) for mid-latitude continental convection. This paper examines oceanic convection and also uses a cloud-resolving model to evaluate these closures.

Geophysical
Fluid
Dynamics
Laboratory

Princeton, New Jersey

Is Cumulus Intensity (Precipitation, Mass Flux) a Simple Function of CAPE?

This closure, or variants based on quantities similar to CAPE, is used in many atmospheric general circulation models,*e.g.*, NCAR CAM (Zhang *et al.*, 1998, *J. Clim.*), GFDL Relaxed Arakawa-Schubert, HadAM3 (Pope *et al.*, 2000, *Clim. Dyn.*), ECMWF (Gregory *et al.*, 2000, *Quart J. Roy. Met. Soc.*)

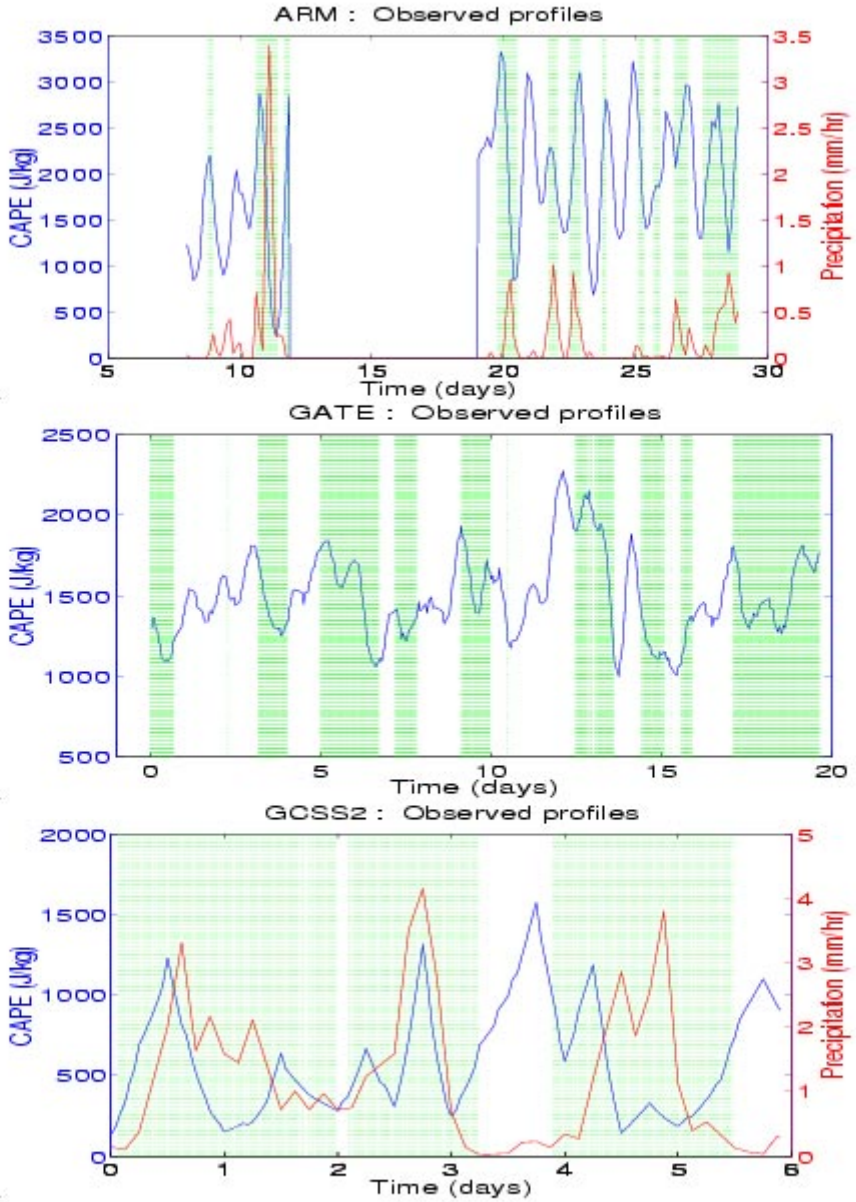
$$CAPE = R_d \int_{LZB}^{LFC} (T_{vc} - \overline{T}) d\ln p$$

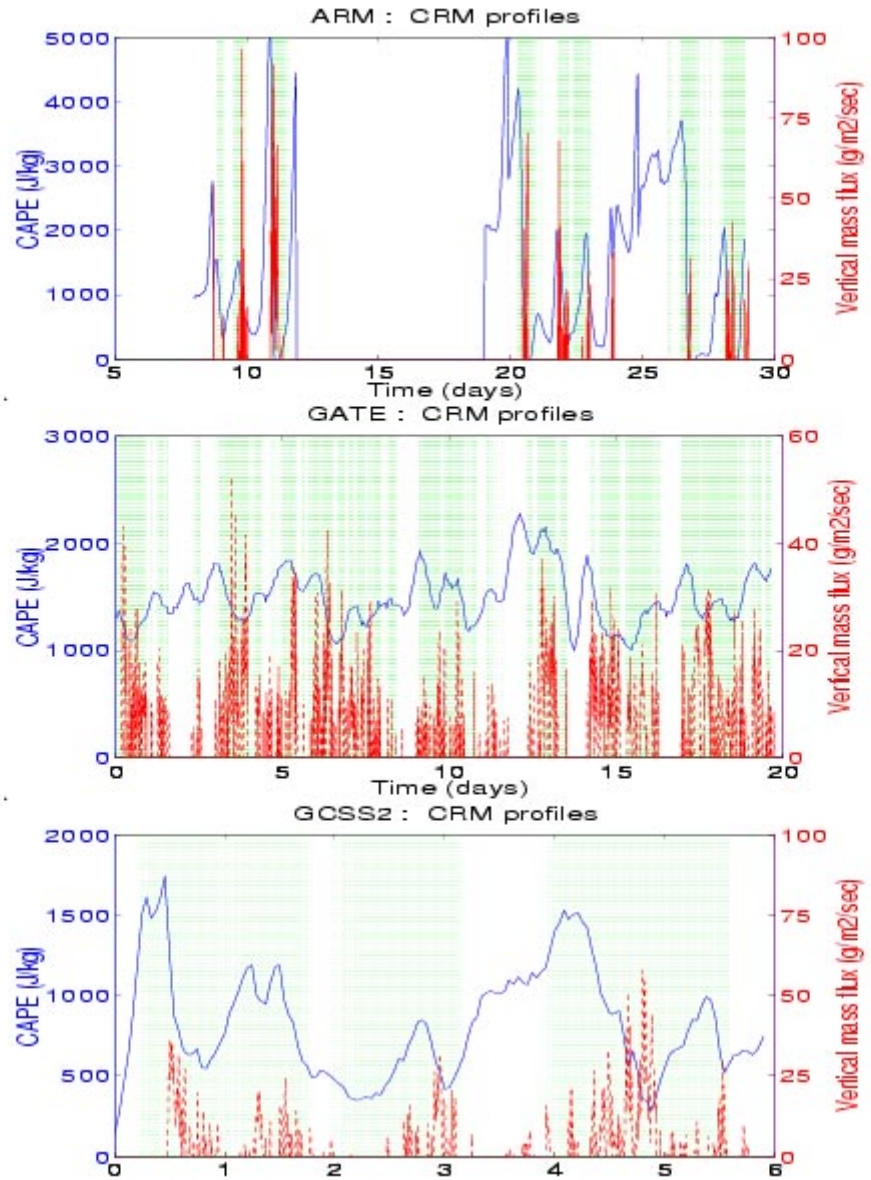
R_d is gas constant; LFC is pressure at level of free convection; LZB is pressure at level of zero buoyancy; T_{vc} is virtual temperature of non-entraining parcel lifted adiabatically from planetary boundary layer; $\overline{T}$ is large-scale temperature; and p is pressure.

Cloud work function is a generalization of CAPE to allow for entrainment into the lifted parcel. HadAM3 uses only near-surface measure of stability instead of full CAPE.

Geophysical
Fluid
Dynamics
Laboratory

Princeton, New Jersey


ARM : Observed profiles
CAPE (J/kg)
Precipitation (mm/hr)
Time (days)
GATE : Observed profiles
CAPE (J/kg)
Time (days)
GCSS2 : Observed profiles
CAPE (J/kg)
Precipitation (mm/hr)
Time (days)


ARM : CRM profiles
CAPE (J/kg)
Vertical mass flux (g/m2/sec)
Time (days)
GATE : CRM profiles
CAPE (J/kg)
Vertical mass flux (g/m2/sec)
Time (days)
GCSS2 : CRM profiles
CAPE (J/kg)
Vertical mass flux (g/m2/sec)

Is Cumulus Intensity Determined by CAPE Equilibrium?

A variant of this closure, based on cloud work function, is used in Arakawa and Schubert (1974, *J. Atmos. Sci.*). Donner (2001, *J. Clim.*) uses CAPE equilibrium.

To evaluate this closure, examine the time evolution of CAPE for mid-continent and tropical oceans. Field data from the ARM, TOGA-COARE, and GATE experiments. It will be useful to think of CAPE as a function of parcel and large-scale variables.

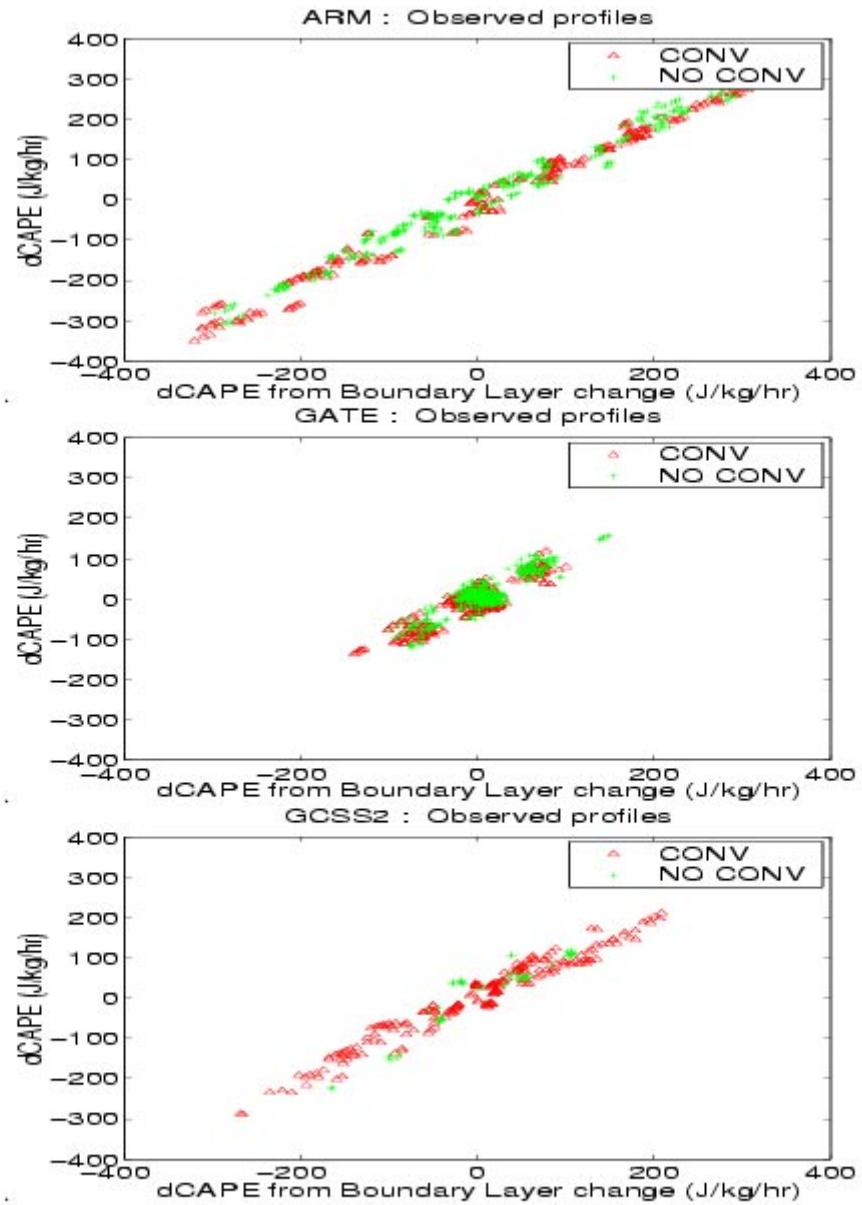
$$CAPE = CAPE(T_{parcel}, q_{parcel}, \bar{T}) = CAPE(T_{pbl}, q_{pbl}, \bar{T})$$

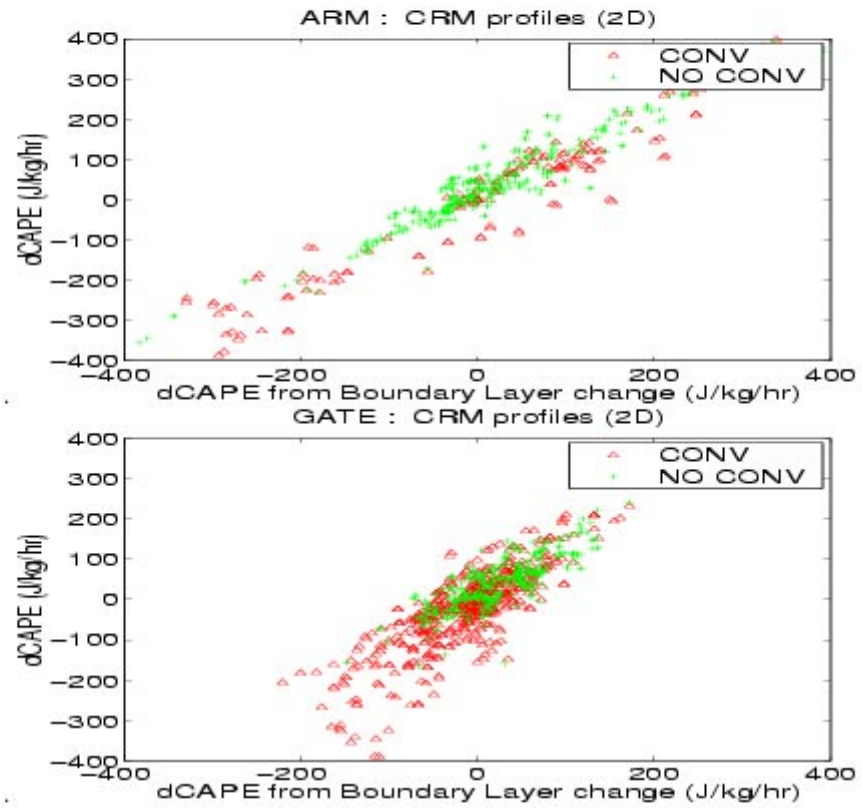
Differentiating,

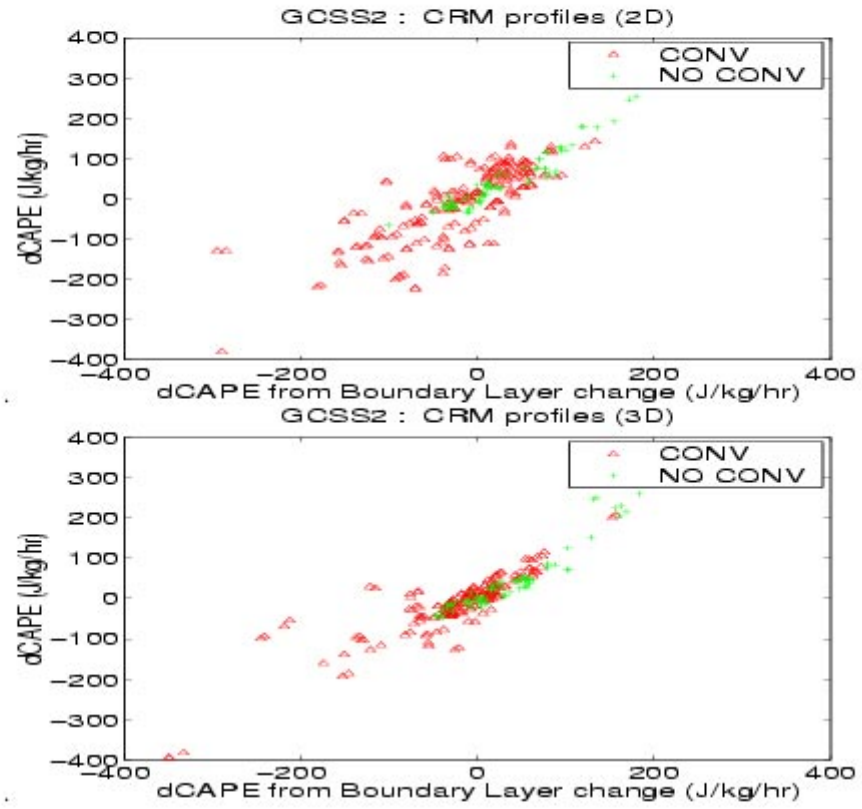
$$\Delta CAPE = \partial CAPE_{PBL} + \partial CAPE_{\bar{T}}$$

Geophysical
Fluid
Dynamics
Laboratory

Princeton, New Jersey


ARM : Observed profiles
CONV
NO CONV
dCAPE (J/kg/hr)
dCAPE from Boundary Layer change (J/kg/hr)
GATE : Observed profiles
CONV
NO CONV
dCAPE (J/kg/hr)
dCAPE from Boundary Layer change (J/kg/hr)
GCSS2 : Observed profiles
CONV
NO CONV
dCAPE (J/kg/hr)
dCAPE from Boundary Layer change (J/kg/hr)


ARM : CRM profiles (2D)
CONV
NO CONV
dCAPE (J/kg/hr)
dCAPE from Boundary Layer change (J/kg/hr)
GATE : CRM profiles (2D)
CONV
NO CONV
dCAPE (J/kg/hr)
dCAPE from Boundary Layer change (J/kg/hr)


GCSS2 : CRM profiles (2D)
CONV
NO CONV
dCAPE (J/kg/hr)
dCAPE from Boundary Layer change (J/kg/hr)
GCSS2 : CRM profiles (3D)
CONV
NO CONV
dCAPE (J/kg/hr)
dCAPE from Boundary Layer change (J/kg/hr)

CAPE Evolution under Deep Cumulus and Implications for Closure

I. CAPE evolution is tightly coupled to planetary boundary layer.

II. CAPE is definitely NOT in equilibrium under deep cumulus convection.

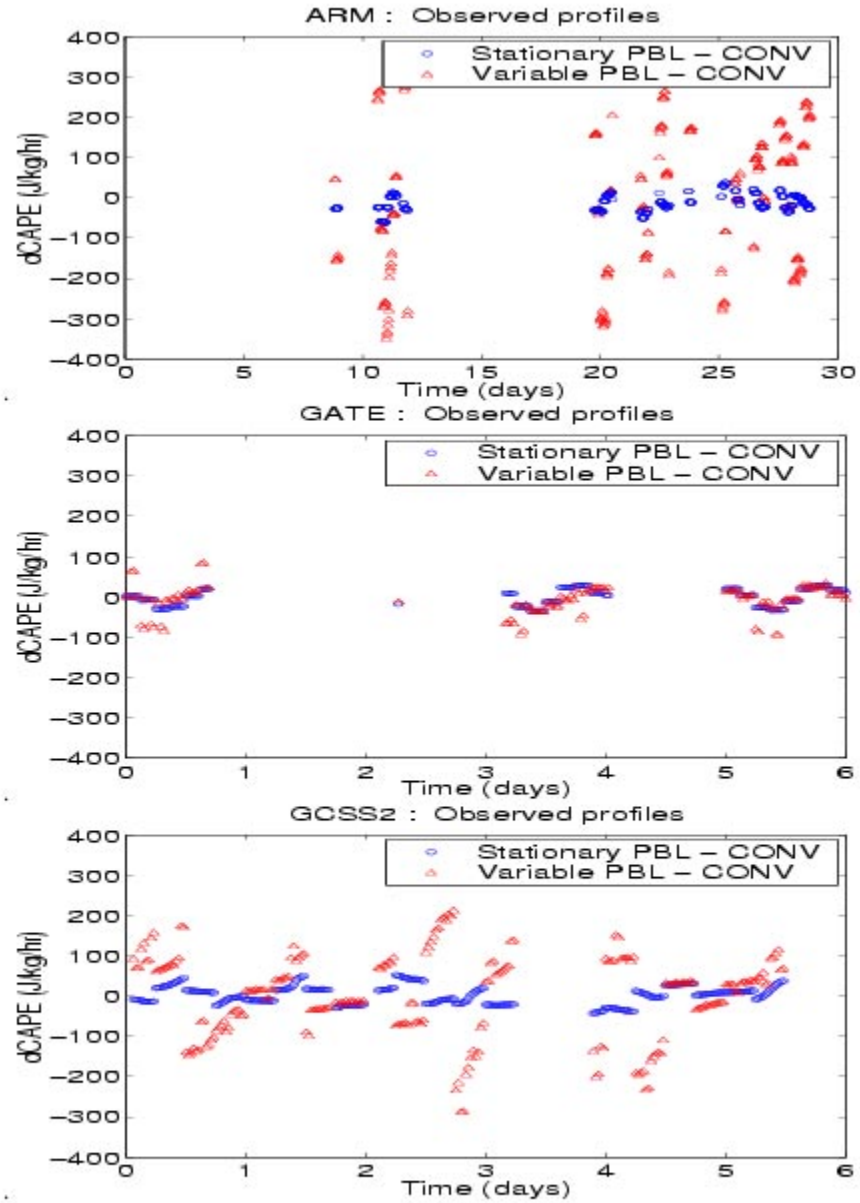
$$\Delta CAPE = \partial CAPE_{PBL} + \partial CAPE_{\overline{T}} \approx \partial CAPE_{PBL}$$

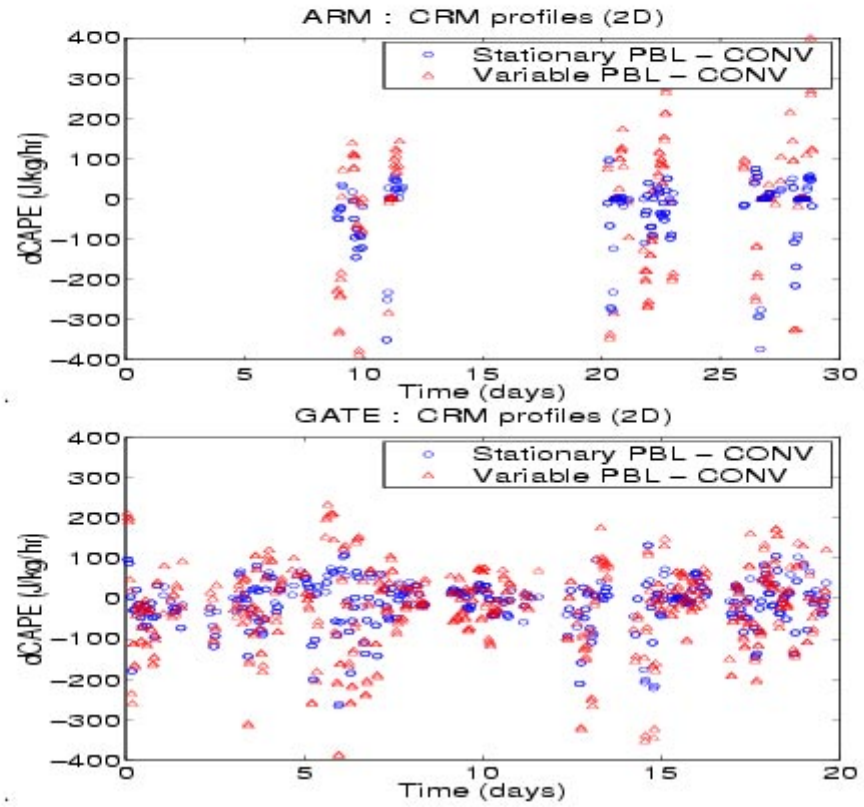
III. As closure, use the approximation (Stationary PBL):

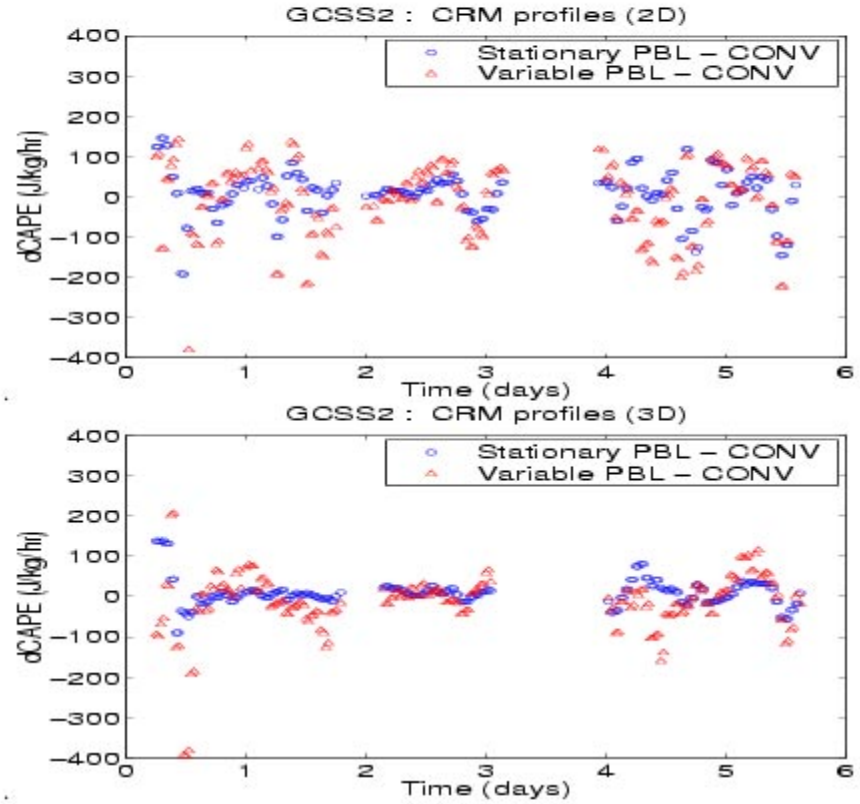
$$\partial CAPE_{\overline{T}} = 0$$

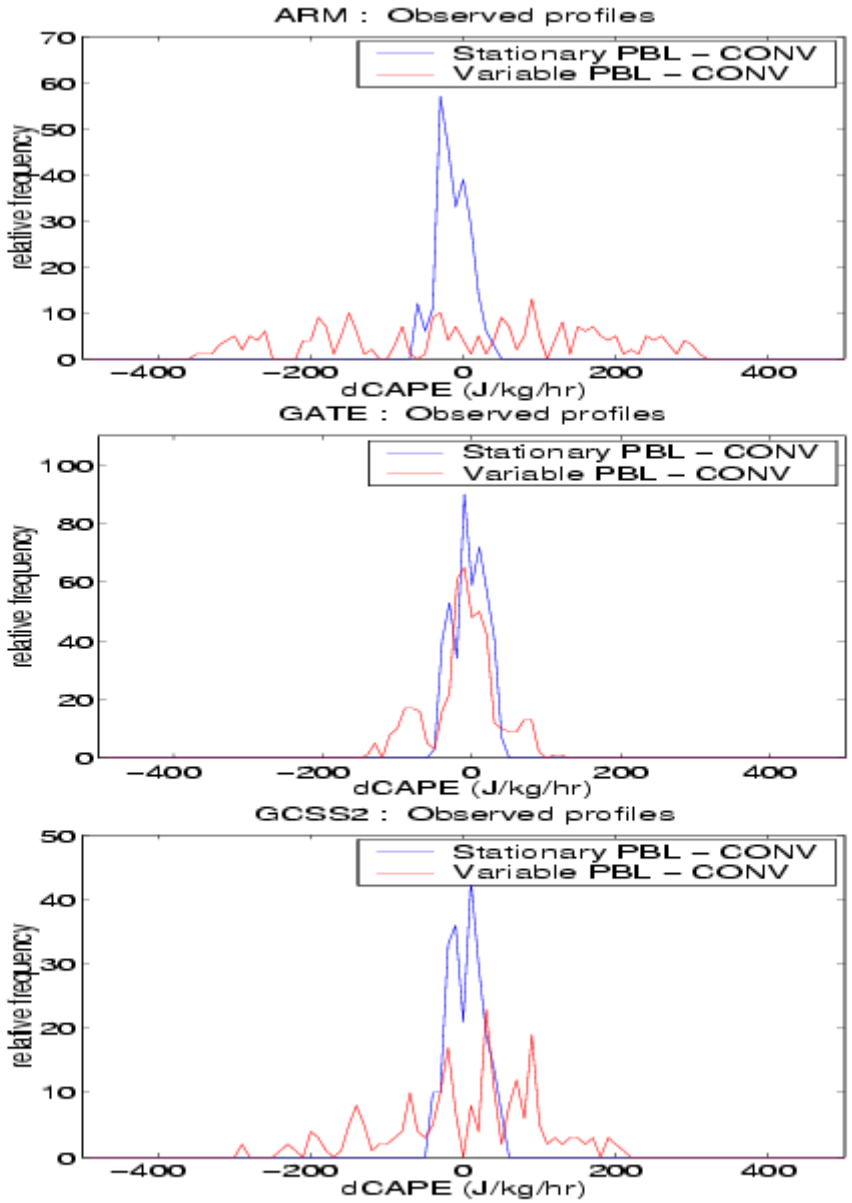
Geophysical
Fluid
Dynamics
Laboratory

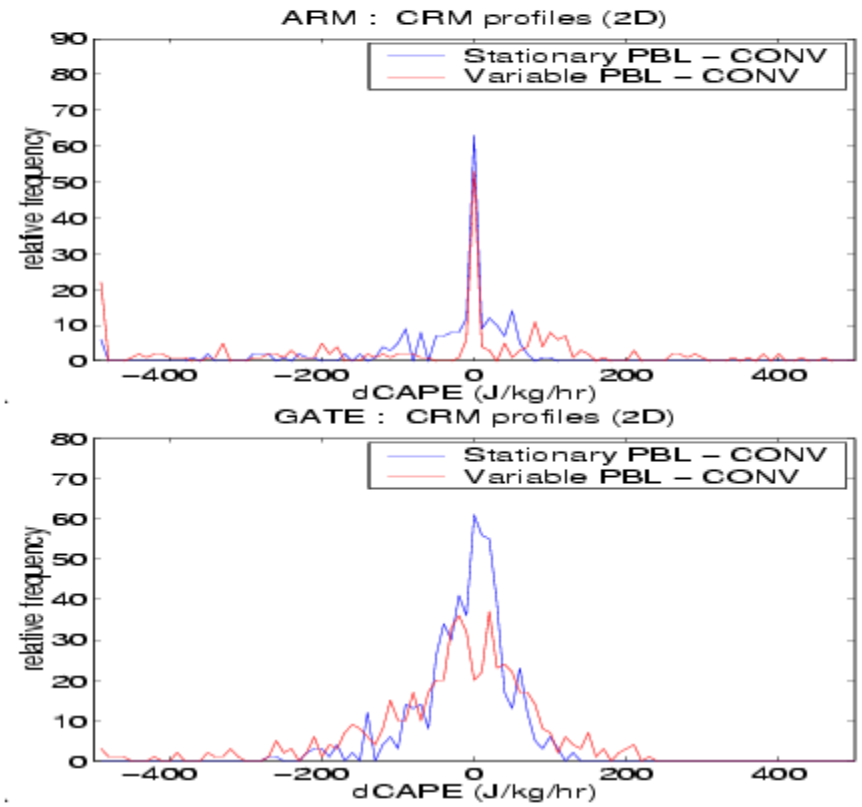
Princeton, New Jersey

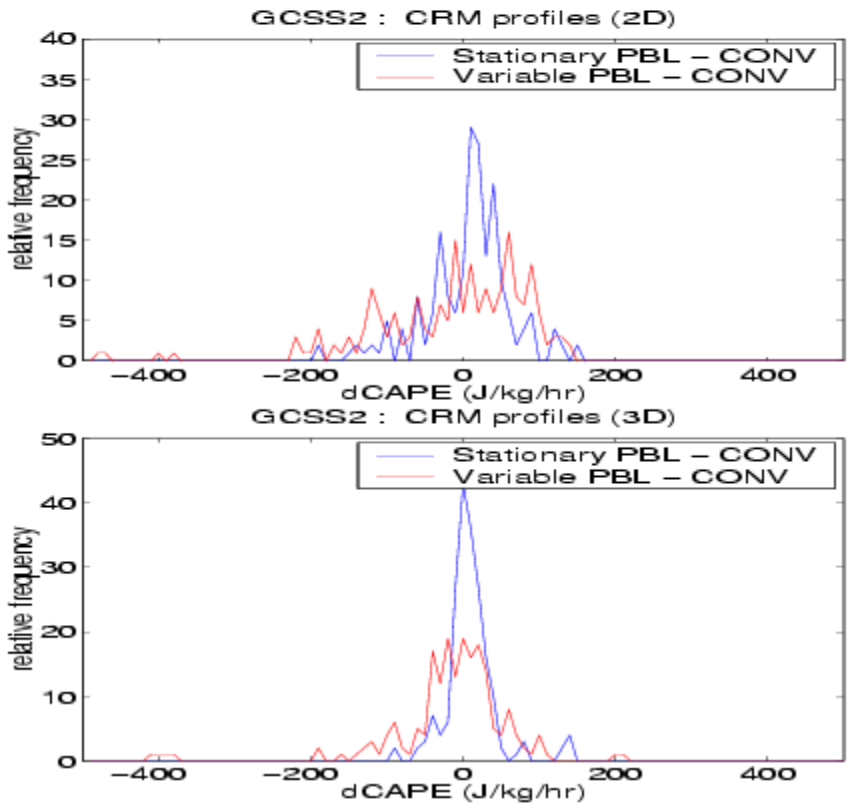

ARM : Observed profiles
Stationary PBL – CONV
Variable PBL – CONV
dCAPE (J/kg/hr)
Time (days)
GATE : Observed profiles
Stationary PBL – CONV
Variable PBL – CONV
dCAPE (J/kg/hr)
Time (days)
GCSS2 : Observed profiles
Stationary PBL – CONV
Variable PBL – CONV
dCAPE (J/kg/hr)
Time (days)


ARM : CRM profiles (2D)
Stationary PBL – CONV
Variable PBL – CONV
dCAPE (J/kg/hr)
Time (days)
GATE : CRM profiles (2D)
Stationary PBL – CONV
Variable PBL – CONV
dCAPE (J/kg/hr)
Time (days)


GCSS2 : CRM profiles (2D)
Stationary PBL – CONV
Variable PBL – CONV
dCAPE (J/kg/hr)
Time (days)
GCSS2 : CRM profiles (3D)
Stationary PBL – CONV
Variable PBL – CONV
dCAPE (J/kg/hr)
Time (days)


ARM : Observed profiles
Stationary PBL – CONV
Variable PBL – CONV
relative frequency
dCAPE (J/kg/hr)
GATE : Observed profiles
Stationary PBL – CONV
Variable PBL – CONV
relative frequency
dCAPE (J/kg/hr)
GCSS2 : Observed profiles
Stationary PBL – CONV
Variable PBL – CONV
relative frequency
dCAPE (J/kg/hr)


ARM : CRM profiles (2D)
Stationary PBL – CONV
Variable PBL – CONV
relative frequency
dCAPE (J/kg/hr)
GATE : CRM profiles (2D)
Stationary PBL – CONV
Variable PBL – CONV
relative frequency
dCAPE (J/kg/hr)


GCSS2 : CRM profiles (2D)
Stationary PBL – CONV
Variable PBL – CONV
relative frequency
dCAPE (J/kg/hr)
GCSS2 : CRM profiles (3D)
Stationary PBL – CONV
Variable PBL – CONV
relative frequency
dCAPE (J/kg/hr)

CAPE Evolution under Deep Cumulus and Implications for Closure

I. CAPE evolution is tightly coupled to planetary boundary layer.

II. CAPE is definitely NOT in equilibrium under deep cumulus convection.

$$\Delta CAPE = \partial CAPE_{PBL} + \partial CAPE_{\overline{T}} \approx \partial CAPE_{PBL}$$

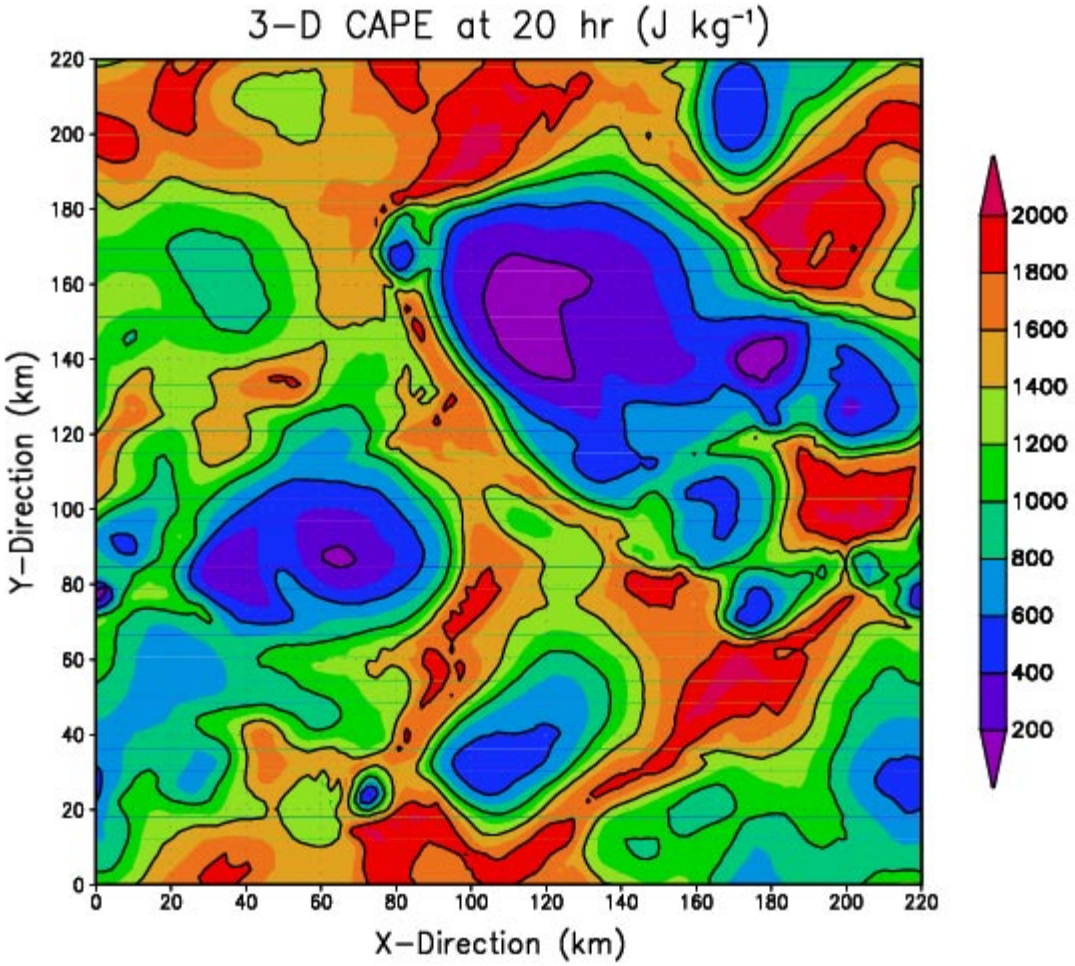
III. As closure, use the approximation (Stationary PBL):

$$\partial CAPE_{\overline{T}} = 0$$

IV. This closure is a better approximation to observations than is CAPE equilibrium. But, is it likely to really be correct?

Geophysical
Fluid
Dynamics
Laboratory

Princeton, New Jersey


3−D CAPE at 20 hr (J kg⁻¹)
Y−Direction (km)
X−Direction (km)
0
20
40
60
80
100
120
140
160
180
200
220
2000
1800
1600
1400
1200
1000
800
600
400
200

Conclusion

I. Cumulus intensity is not simply related to CAPE (or cloud work function), challenging closures in many major GCMs.

II. CAPE evolution under deep cumulus convection is driven primarily by large changes in the planetary boundary layer. The relative smallness of CAPE changes due to temperature changes above the boundary layer provides a closure in better agreement with observations and CRM results than CAPE quasi-equilibrium. Results of Zhang (2002, *JGR*) largely confirmed.

III. CRMs suggest individual cumulus parcels "see" local CAPE values that differ by many factors from the large-scale CAPE. Large-scale CAPE by itself is not ultimately a good candidate for closure.

IV. CAPE is fundamentally not in equilibrium under deep cumulus.

"If we were in equilibrium, we would not only be dead-we would be homogeneous!" ...Sidney Nagel (2002), "Physics in Crisis"

Geophysical
Fluid
Dynamics
Laboratory

Princeton, New Jersey