CAM6 Deep Cumulus Parameterization

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CAM6 Deep Cumulus Parameterization: Structure of Problem

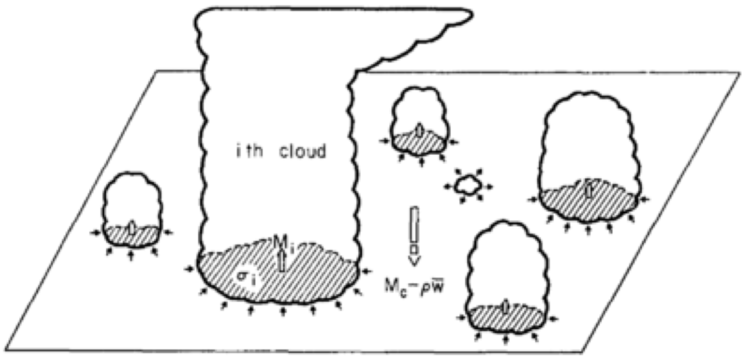

FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

References:
Arakawa and Shubert (1974, *J. Atmos. Sci.*)
Zhang and McFarlane (1995, *Atmosphere-Ocean*)

$$\bar{\rho}\frac{\partial \bar{s}}{\partial t} + \nabla\cdot(\overline{\rho \mathbf{v} s}) + \frac{\partial}{\partial z}(\overline{\rho w s}) = \bar{Q}(Phase\ Changes) + \bar{Q}_R$$

$s = c_p T + g\,z$, dry static energy

overbar – grid mean

Structure of Problem

$$1 = a_u + a_d + a_e$$

$$M_u = \rho_u \, w_u \, a_u$$

$$M_d = \rho_d \, w_d \, a_d$$

$$M_c = M_u + M_d$$

$$\bar{\rho}\,\frac{\partial \bar{s}}{\partial t} + \nabla \cdot \left(\overline{\rho \mathbf{v} s}\right) \; = \; -\frac{\partial}{\partial z}\left(M_u S_u + M_d S_d + \bar{\rho} a_e w_e \bar{s}\right)$$

$$+ \, \bar{Q}(Phase\ Changes) + \bar{Q}_R$$

$$\overline{\rho w} = \bar{\rho} a_e w_e + M_c$$

$$\bar{\rho}\frac{\partial \bar{s}}{\partial t} + \nabla \cdot (\overline{\rho \mathbf{v} s}) = -\frac{\partial}{\partial z}\left[M_u S_u + M_d S_d + \bar{s}(\overline{\rho w} - M_c)\right]$$

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$$\bar{\rho}\frac{\partial \bar{s}}{\partial t} + \nabla \cdot \left(\vec{\boldsymbol{V}}\, \overline{s\rho}\right) + \frac{\partial}{\partial z}(\overline{\rho w s}) = -\frac{\partial}{\partial z}(M_u S_u + M_d S_d - \bar{s} M_c) + \bar{Q}(Phase\ Changes) + \bar{Q}_R$$

Structure of Problem

$$C_p\left(\frac{\partial \bar{T}}{\partial t}\right)_{Cu} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left(M_u S_u + M_d S_d - \bar{s} M_c\right) + Q(Convective\ Phase\ Changes) + Q_R(Convective\ Clouds)$$

Also,

$$\left(\frac{\partial \bar{q}}{\partial t}\right)_{Cu} = -\frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\left(M_u q_u + M_d q_d - \bar{q} M_c\right) + \ldots$$

Similarly, for tracers, horizontal momentum, microphysics.

Deep cumulus parameterization provides:
M_u, M_d, $M_u S_u$, $M_d S_d$, $M_u q_u$, $M_u q_d$,
convective phase changes, ...

Updrafts , M_u

Reference: Zhang and McFarlane (1995, *Atmosphere-Ocean*)

Updrafts are an ensemble of entraining plumes:

$$\frac{1}{m}\frac{dm}{dz} = \lambda$$

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Defining Assumption: An alternate is GFDL AM4 (Zhao *et al.*, 2018a,b, *JAMES*) which uses a variant of Bretherton *et al.'s* (2004, *Mon. Wea. Rev.*) buoyancy-sorting, entrainment-detrainment plume.

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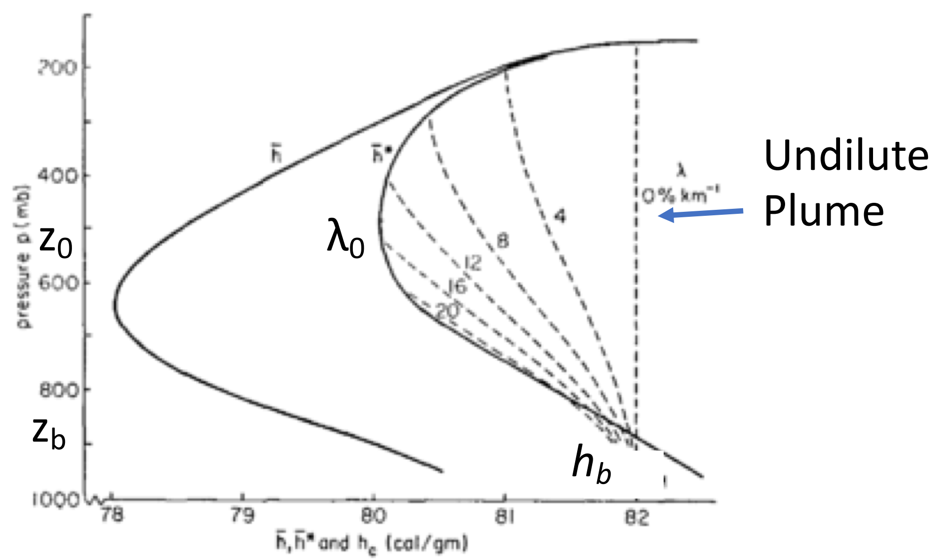
Deep plumes extend above minimum in grid-mean saturated moist static energy $\bar{h}^* = c_p\bar{T} + g\,z + L\,q_{sat}(\bar{T})$



based on Arakawa and Schubert (1974, *J. Atmos. Sci.*)

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Assume $m_b(\lambda)$ independent of λ ->
Same base mass flux for all ensemble members

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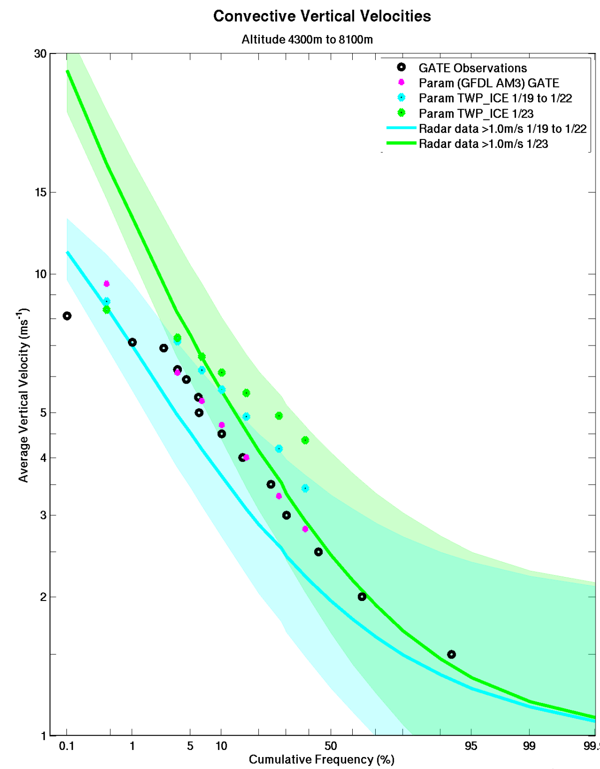
Defining Assumption: An alternate is GFDL AM3, where the base mass fluxes vary strongly among ensemble members, constrained by observations of updraft vertical velocities (Donner, 1993, *J. Atmos. Sci.*).



GFDL AM3 single-column & Dual-Doppler TWP-ICE (Collis *et al.*, 2013) Vertical Velocities

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λ_0 : largest entrainment rate, for plume with zero buoyancy at $\bar{h}^*$ minimum

$\lambda_D(z)$: entrainment rate for plume with zero buoyancy at z

$\lambda_D(z_0) = \lambda_0$

If all plumes have same base mass flux, total ensemble mass flux at z is

$$M_u(z) = M_b \int_0^{\lambda_D} \frac{1}{\lambda_0} e^{\lambda(z-z_b)} d\lambda$$

$$= \frac{M_b}{\lambda_0(z-z_b)} \left[e^{\lambda_D(z-z_b)} - 1\right]$$

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Solve for λ_D :

$$h_b - h^* = \lambda_D \int_{z_b}^{z} [h_b - h(z')]\, e^{\lambda_b(z'-z)} dz'$$

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$$\boxed{\begin{array}{c} M_b, M_u, \lambda_D \text{ and plume equations can be used to determine} \\ \text{updraft} - \text{related parameterization outputs.} \end{array}}$$

Ensemble Downdraft Mass Flux , $\mathrm{M_d}$

Proportional to Cloud-Base Mass Flux

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Downdrafts

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- μ specified (~ 0.2)

Cloud-Base Mass Flux , M_b

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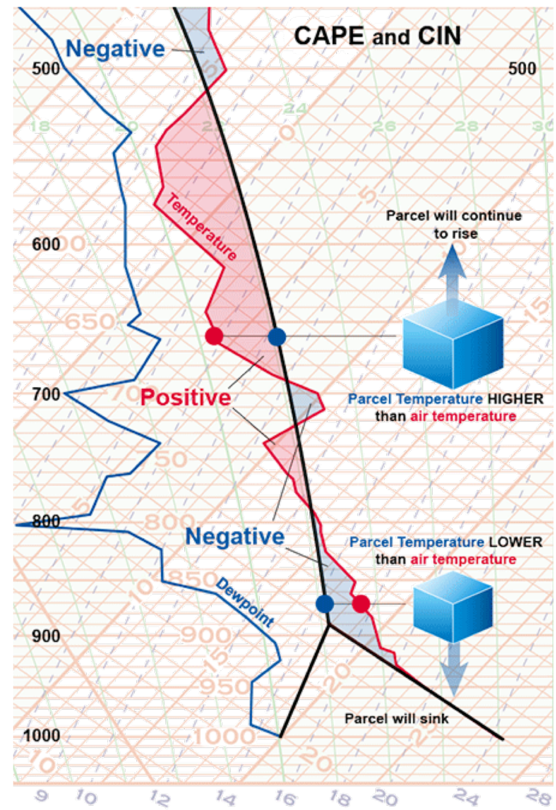
θ_v is virtual potential temperature
subscript in θ_{vp} indicates parcel

$$\left.\frac{\partial CAPE}{\partial t}\right)_{Cu} = -M_b F$$



cape.png from NWS JetStream Max: Severe Weather :
https://www.weather.gov/jetstream/skewt_severe_max

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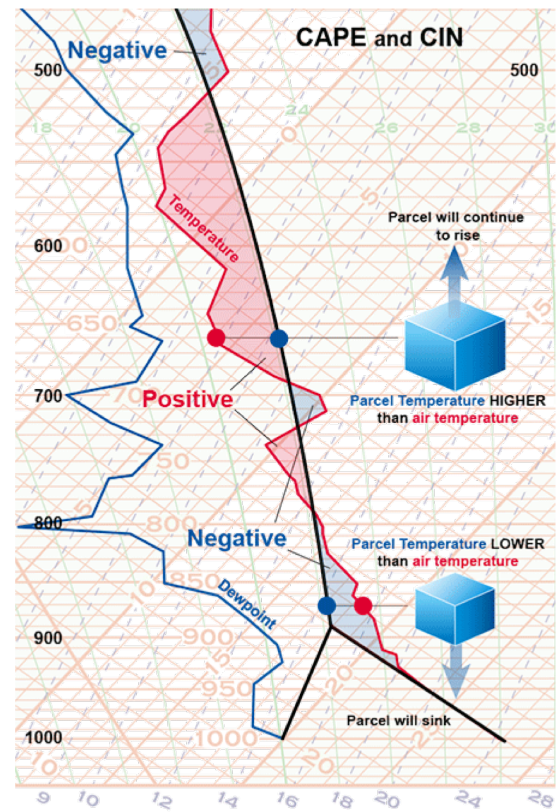
obtain F by differentiating CAPE integral, making use of $\left.\frac{\partial \bar{T}}{\partial t}\right)_{Cu}$ and $\left.\frac{\partial \bar{q}}{\partial t}\right)_{Cu}$



cape.png from NWS JetStream Max: Severe Weather :
https://www.weather.gov/jetstream/skewt_severe_max

Closure Assumption: Convection consumes CAPE generated by large-scale processes, e.g., radiative cooling and advection ("quasi-equilibrium"). Approximate as ${}^{CAPE}/_{\tau}$, where τ is an imposed relaxation time scale.

So, $$M_b = -\frac{CAPE}{\tau F}$$

Bulk Plume Microphysics and Phase Changes

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- l : ensemble mean liquid water
- Terms proportional to M_b
- P, precipitation, $P = C_0 M_b\, l$
- C_0, autoconversion of cloud condensate to precipitation

CAM Extensions / Modifications to Zhang – McFarlane Parameterization

- *Deep Convective Horizontal Momentum Transport* (Richter and Rasch, 2008, *J Clim*)

$$\left.\frac{\partial\bar{\boldsymbol{V}}}{\partial t}\right)_{Cu} = -\frac{1}{\rho}\frac{\partial}{\partial z}\left(M_u\boldsymbol{V}_u + M_d\boldsymbol{V}_d - M_c\boldsymbol{V}\right)$$

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$$-\frac{1}{\rho}\frac{\partial}{\partial z}\left(M_d\boldsymbol{V}_d\right) = E_d\boldsymbol{V} + \vec{P}_G^{\,d}$$

with pressure-gradient forces:

$$\vec{P}_G^{\,u} = -\,C_u M_u \frac{\partial \boldsymbol{V}}{\partial z}$$

$$\vec{P}_G^{\,d} = -\,C_d M_d \frac{\partial \boldsymbol{V}}{\partial z}$$

C_u, C_d tunable parameters

- *Deep Convective Tracer Transport*

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$$x \in (u, d)$$

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- *CAM6 tuned to increase sensitivity to convective inhibition*