UNIFYING REPRESENTATION OF THE PLANETARY BOUNDARY LAYER AND SHALLOW CUMULUS CONVECTION

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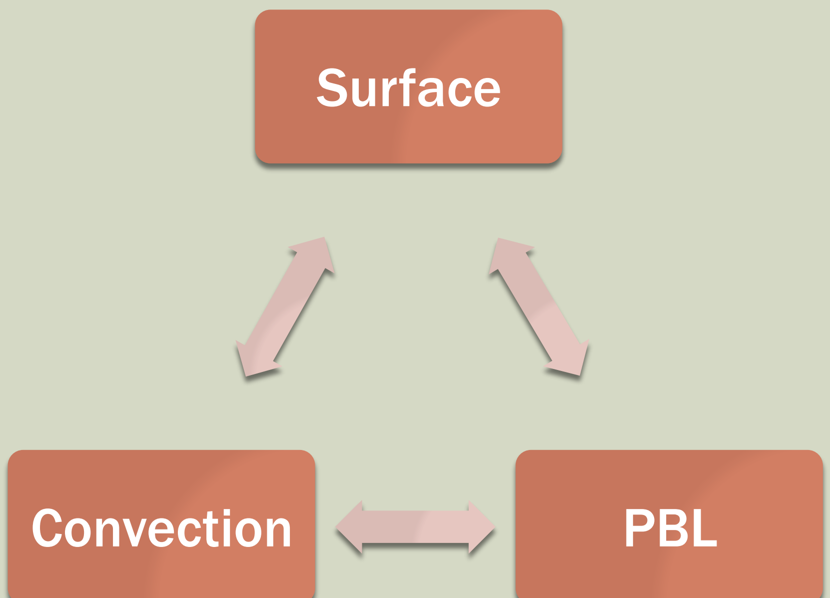
Theoretical considerations for modeling

INTRODUCTION

- Cumulus clouds are simply buoyant thermals with sufficient energy to overshoot the PBL and condense.
- Cumulus convection therefore acts as a local extension of the PBL into the free atmosphere.
- However, conventional atmospheric models treat the PBL and shallow cumulus convection (SCU) separately.
- A unified PBL-SCU scheme is a natural approach.

IMPORTANCE OF COUPLING

- Surface flux drives PBL turbulence.
- Buoyant, turbulent thermals become cumulus clouds.
- Cloud cover modulates surface fluxes via shortwave radiation.



RESEARCH GOALS AND THEMES

- Develop a unified PBL-SCU scheme for CWRF/WRF.
- PBL-SCU physics based on process level understanding. Avoid parameterization, similarity-based scaling, and tuning wherever possible. ***Get things right for the right reason.***
- Incorporate unified model of dry and moist thermals. Follow thermals from the surface to their tops as cumulus clouds.
- Stochastic Model: the statistics of thermals at various altitudes determines convective transport. Must be based on sound probabilistic reasoning.
- Must be valid across multiple scales since boundary layer clouds occur at a variety of scales.

THERMAL/PLUME MODELS AND MASS FLUX APPROACH

- Mass and turbulent flux:

$$\frac{dM}{dz} = \left(\varepsilon - \delta\right) M \qquad \rho \overline{w^{'} \phi^{'}} = M \left(\phi - \overline{\phi}\right)$$

- Entraining plume model:

$$\frac{d\phi}{dz} = -\varepsilon \left(\phi - \overline{\phi}\right) \qquad \phi \in \left\{\theta_l, q_t\right\}$$

- Momentum/Kinetic Energy:

$$\frac{1}{2} \frac{dw^2}{dz} = c_1 g \frac{\theta - \overline{\theta}}{\overline{\theta}} - c_2 \varepsilon w^2$$

ISSUES WITH TRADITIONAL APPROACH

- Detrainment rate depends heavily on presence of liquid water due to presence evaporative cooling. Cannot simultaneously represent dry thermals in sub-cloud layer.

- Nonlinearity associated with condensation erodes ability of single bulk plume to predict statistics of convective transport. (ex: cloud top height)

$$E\left[f\left(x\right)\right] \neq f\left(E\left[x\right]\right)$$ **when f is nonlinear**

- Single entraining plume model cannot represent individual clouds (Warner's paradox). Better suited for *ensemble of cumulus clouds in equilibrium with large-scale environment*. Not valid across multiple temporal and spatial scales.

MULTIPARCEL APPROACH

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- Neggars and Siebesma 2002 developed a multiparcel model of convection.

$$M_i = \sigma_i \rho w_i \qquad M = \sum_{i=1}^{n} M_i \qquad \overline{w'\phi'} = \sum_{i=1}^{n} M_i \left(\phi_i - \overline{\phi}\right)$$

- Based on buoyancy sorting hypothesis: when a parcel becomes negatively buoyant, it leaves the cloud/thermal and detrains at level of nuetral buoyancy.

- No need for detrainment rate.

- Derived dynamic entrainment rate, based on physical principles, which acts on parcel scale and validated using LES.

$$\varepsilon = \frac{1}{\tau w} \qquad \tau = 400s$$

- **Theoretically valid across multiples scales.**

PROBABILISTIC BULK CONVECTION MODEL

- Gentine et al. 2013: Idealized bulk model PBL and cumulus layer profile.
- Ensemble of buoyant parcels released at top of surface layer according to joint PDF of $\{\theta, q, w\}$
- PBL entrainment velocity:

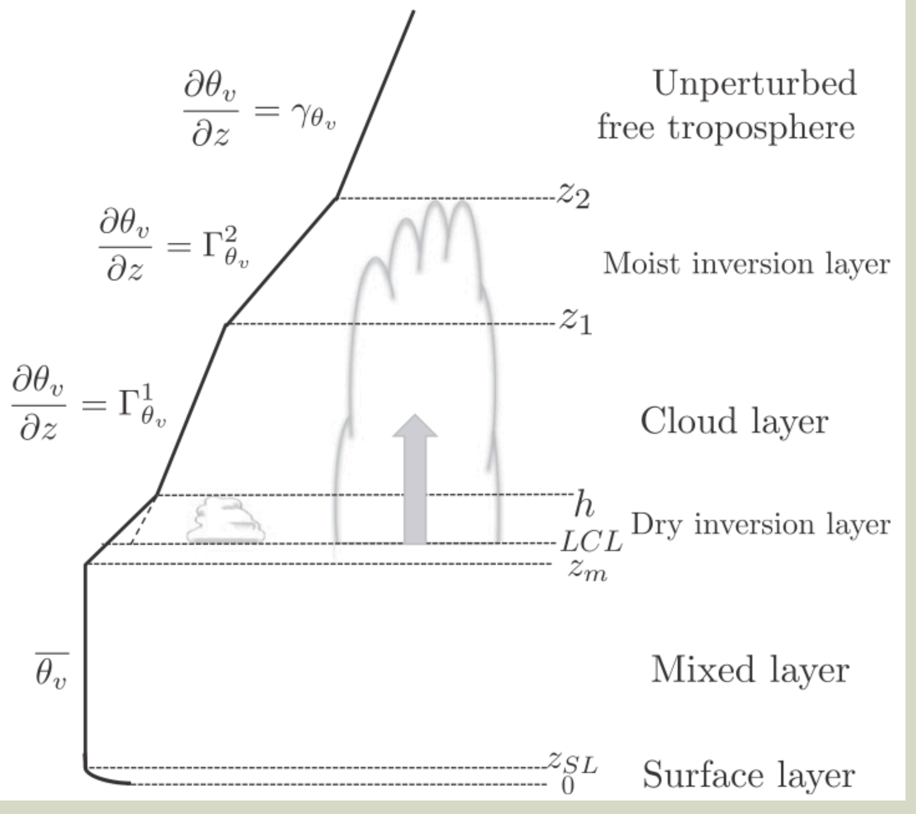
$$\frac{dh}{dt} = \frac{1}{\rho}\left[M(h) - M_{active}(h)\right]$$

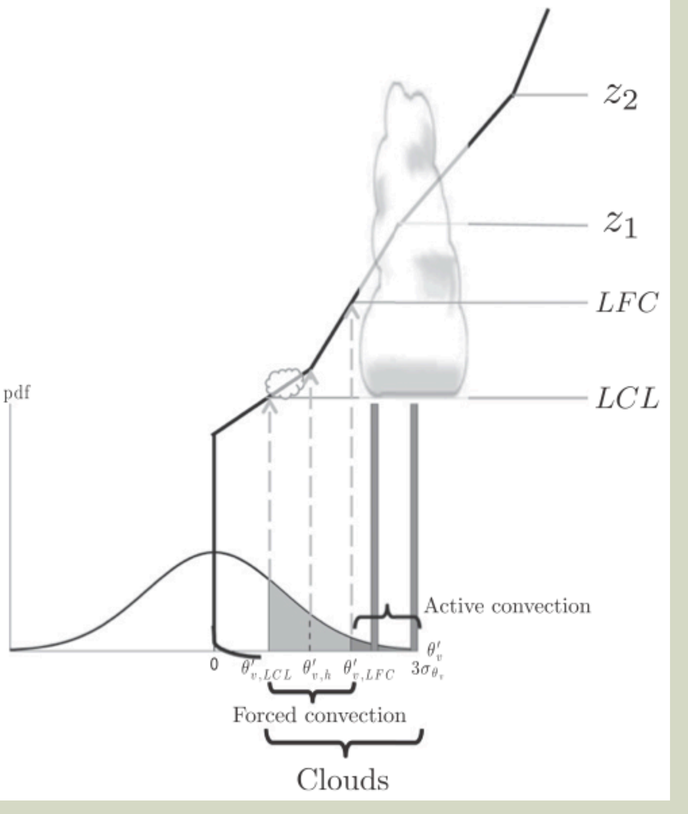
M_{active} mass flux of parcels which reach LFC. Essentially cloud base mass flux.

- Heat and moisture transport out of PBL by active parcels accounted for in top of PBL flux.
- Single bulk entraining/detraining plume used in cumulus layer

PROBABILISTIC BULK CONVECTION MODEL

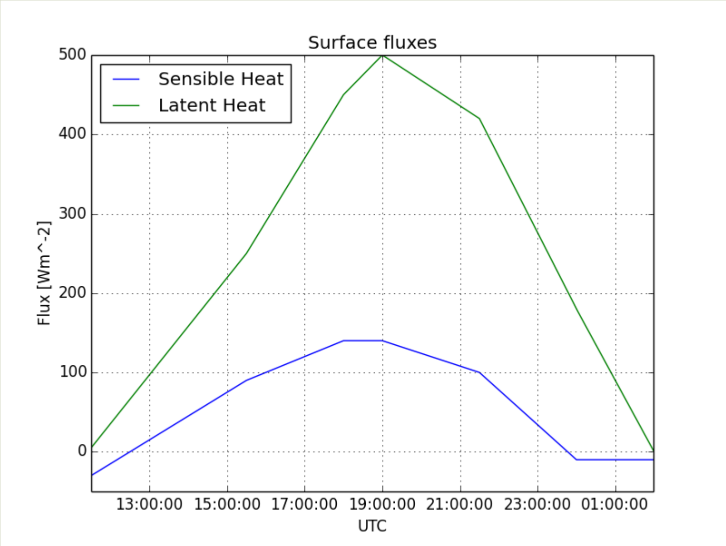
- From Gentine et al. 2013:

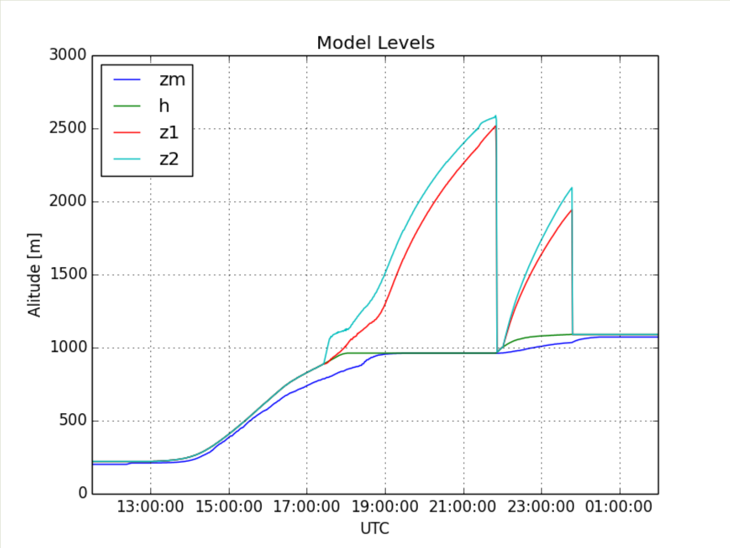




IMPLEMENTATION PROGRESS

- Code used for published results on lead author's website does not follow published specifications of model. Reproducing results remains a challenge if specification followed faithfully.
- Southern Great Plains, ARM Central Facility, June 21 1997





FUTURE WORK

- Fix entrainment zone depth closure to avoid entrainment zone collapse in simulations.
- Bulk profile not realistic. Build PBL-SCU scheme with turbulent mixing (perhaps 1.5 order turbulence and EDMF) but with entrainment velocity based on PBCM closure principle.
- PBCM uses single bulk parcel in cumulus layer. Build PBL-SCU scheme based on complete multiparcel approach.