Mixing, Buoyancy, and Vertical Velocity Statistics in a CRM Simulation of West Pacific Deep Convection, and Implications for Cumulus Parameterizations for Climate Models

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Cumulus parameterization and tropical rainfall biases

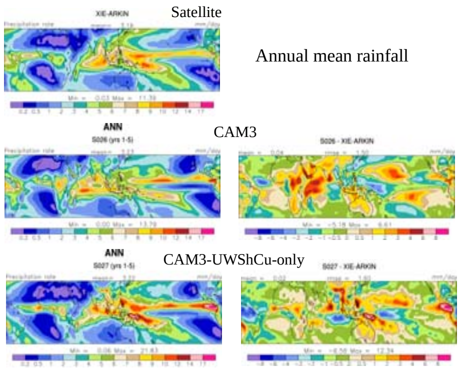
We have developed a new bulk parameterization for shallow (weakly precipitating) cumulus convection based on Bretherton et al. (2004, MWR) and implemented it in the CAM3 climate model. Our ARM-sponsored research aims to extend this parameterization to deep convection, guided by cloud-resolving modeling and observations.

UWShCu parameterization features

- Kain-Fritsch-like cloud updraft, lateral mixing $\propto z^{-1}$ with buoyancy-sorting.
- Mass flux/triggering based on convective inhibition, PBL TKE.
- Simple microphysics (rainout of updraft condensate > 1 g kg^{-1}).
- Fixed fraction of precipitation detrained to environment, no explicit downdraft
- Cu momentum transport following Innes and Gregory.

Climate improved using UWShCu for deep Cu too

Preliminary CAM3 simulations with UWShCu also used for deep convection (left) already have better geographical rainfall distribution than CAM3 with UWShCu called after default Zhang-MacFarlane deep convection scheme (right). Excess rainfall in central Pacific, Arabia are suppressed. However, rainfall is too strong over W Pacific, and too weak over Amazonia, suggesting further improvements are needed.



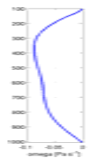
Thanks ...to Peter Blossey (UW) for running SAM, Marat Khairoutdinov for providing SAM, Jennifer Fletcher for plots, and grant DE-FG02-05ER63959 for support.

Atmospheric Sciences, University of Washington — ARM Atmospheric Radiation Measurement

Tropical Oceanic Convection CRM Test Case

A CRM simulation of idealized quasi-steady W Pacific warm pool deep convection provides stable, easily-interpreted statistics and an easy comparison with the single-column CAM3 (SCAM3):

- SST = 302.9 K, at equator (f = 0).
- Mean wind nudged to 5 m s^{-1} at surface, linearly decreasing above.
- Mean ω (right) from ERA40 warm pool composite, scaled to make mm d^{-1} rainfall.



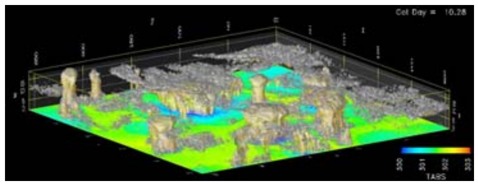
SAM6.4 cloud-resolving model (Khairoutdinov and Randall 2003): 96 vertical levels, $\Delta x = \Delta y$ = 1 km,

Interactive diurnally-averaged 1 Jan. radiation.

Latent heat of freezing set to zero; Model equations for advection and moist processes exactly conserve MSE $h = c_pT + gz + Lq$.

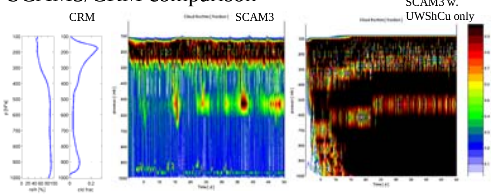
Run 50 days on doubly-periodic 64x64 domain to near-steady state, then 10 more days on a 256x256 km domain for this analysis.

A snapshot of the CRM-simulated cloud field



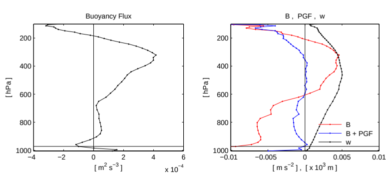
Cloud water/ice > 0.1 g/kg (silver), precipitating water/ice > 0.5 g/kg (gold), near-surface air temperature (color) - shows a realistic mixture of active deep cumuli, stratiform convection, and thinner cirrus anvil, producing realistic TOA LW, SW cloud-radiative forcing:

SCAM3/CRM comparison



The CRM cloud fraction (left) is much less than in SCAM3. With UWShCu only, not enough convection reaches the upper troposphere to prevent near-saturation at all levels down to the surface – a poor simulation begging for improvement.

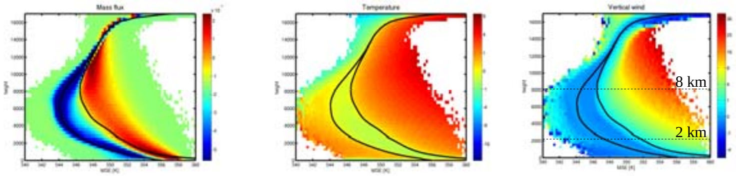
Interesting puzzle: 'Average' Cu updrafts are not buoyant!



Although the buoyancy flux is positive at most levels above cloud base, the average buoyancy of saturated cumulus updrafts is *negative* in the lowest 4 km! Perturbation upward pressure gradient forces compensate; updrafts also accelerate by systematically detraining their slowest air.

MSE-binned analysis of CRM simulation

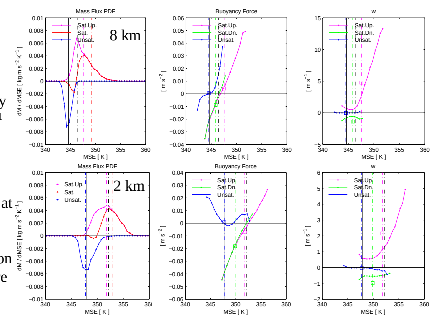
Following Kuang and Bretherton (JAS, 2006), we bin all gridpoints at each height level of all 240 hourly 3D volumes saved from the 10-day simulation by moist static energy. MSE is conserved by advection and model microphysics, so over cumulus lifecycles, MSE is mainly affected by turbulent mixing and is an excellent entrainment tracer. In saturated air, MSE determines the temperature, which is the main contributor to air density and buoyancy. The plots below show the power of this approach. The results are directly comparable to similarly-plotted results of both bulk and plume-ensemble cumulus parameterizations. Black lines are horizontal-mean MSE and saturation MSE profiles. For saturated air, temperature perturbation is proportional to the difference of the local MSE from hor-mean sat. MSE. Above cloud base, higher MSE corresponds to less entrainment dilution of updraft air. Most (but not all) upward mass flux is in dilute, barely buoyant, weak updrafts.



Interesting features of MSE-binned results and parameterization implications.

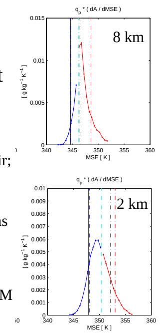
1. Downdrafts?

- Downdrafts tend to have higher than ambient MSE.
- Saturated downdrafts typically have velocity less than 1 m s^{-1} and are thermodynamically similar to saturated updrafts (including buoyancy).
- There is a threshold MSE h_{zm} at which net mass flux changes sign; MSE > h_{zm} provides a good thermodynamic definition of cumulus updraft to compare with parameterizations



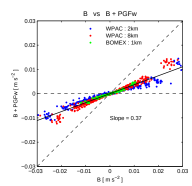
2. Precipitation partitioning between Cu (red) and ambient (blue) air.

- In lower troposphere, most precip falls in unsaturated air; reverse holds in upper troposphere.
- Evaporating precip. moistens and cools the cloud environment. This is an important 'knob' in Cu parameterizations such as ZM and UWShCu.



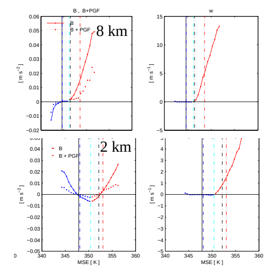
3. Buoyancy and vertical PGF.

- About 60% of air parcel buoyancy B is opposed by vertical pressure gradients PGFw for both saturated and unsaturated air in both shallow and deep cumulus ensembles (each point at right bins 3000 gridpoints of similar buoyancy.) This effect, not currently in UWShCu, is useful for formulating a Cu updraft w eqn.



4. Evaporative cooling and buoyancy sorting

- At 'Cu updraft' MSEs > h_{zm} (red), buoyancy and vertical velocity increase with MSE. For 'ambient' MSEs < h_{zm}, w is near zero and lower-trop. B decreases with MSE, reflecting mixing-induced evaporative cooling.
- Our UWShCu buoyancy-sorting algorithm underpredicts the fraction of mixtures retained in the updraft and will be improved based on this CRM analysis.



Conclusions

- MSE-binning of CRM-simulated deep convection effectively extracts key properties of the cloud ensemble and provides useful physical realizations useful for improving bulk and spectral Cu params:
  - explicit downdrafts less important than 'detraining' precipitation
  - vertical PGF reduces effective buoyancy by 2/3
  - vertical velocity-buoyancy proportionality in updrafts.
- Next: analyze wider range of cases, esp. well-observed continental convection (SGP & TWP-ICE).