Augmenting the double-Gaussian representation of atmospheric turbulence and convection via a coupled stochastic multi-plume mass flux scheme

CL08

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A new path toward unification of subgrid processes in global models

- It is increasingly common to unify parameterization of sub-grid scale vertical motions (i.e., PBL turbulence and shallow convection) and cloud macrophysics because of the close coupling of small-scale dynamics and cloud processes
- We adapt the Eddy Diffusivity/Mass Flux (EDMF) framework to couple an assumed PDF higher order closure (CLUBB) and a stochastic multi-plume mass flux (MF) scheme in CAM6
- This scheme is specifically intended to ameliorate known issues with the double Gaussian representation of subgrid variability in representing moist convection due to underprediction of skewness
- Here, we outline the approach and show results from our implementation of the new scheme CLUBB+MF in the single column configuration of the model, SCAM6

Implementation of CLUBB+MF in CAM

The basic premise of the EDMF approach adopted here is that the total turbulent flux of a generic scalar (φ) is the sum of contributions from CLUBB and MF, which represent mixing due to the non-convective environment and coherent updrafts, respectively:

$$\overline{w'\varphi'} = \overline{w'\varphi'}_{CLUBB} + \sum_{i=1}^{N} a_i (w_i - \overline{w})(\varphi_i - \overline{\varphi})$$

where the CLUBB flux is a prognostic variable, *N* is the number of plumes per gridbox, a_i is the fractional area of the i-th plume, w_i and φ_i are plume vertical velocity and scalar value, and overbars denote a spatial mean.

As MF plumes are diagnostic, we incorporate their contribution to the total flux as an explicit term within CLUBB's diffusion solver:

$$\frac{\overline{\varphi}^{t+\Delta t}}{\Delta t} + \frac{1}{\rho}\frac{\partial}{\partial z}\rho\overline{w'\varphi'}^{t+\Delta t}_{CLUBB} = \frac{\overline{\varphi}^{t}}{\Delta t} - \frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho \sum a_i w_i \varphi_i'\right)^{t}_{MF} + \left.\frac{\partial\overline{\varphi}}{\partial t}\right|_{forcing}$$

Plumes are modeled following Suselj et al. (2019). Initial conditions are drawn from an assumed Gaussian distribution, the width of which is determined by surface flux magnitude. The vertical evolution of *w* in the i-th plume is given by:

$$\frac{1}{2}\frac{\partial w_i^2}{\partial z} = aB_i - b\varepsilon_i w_i^2$$

where *a* and *b* are constants, B_i is buoyancy, and ε_i the entrainment rate, which is stochastically drawn from a Poisson distribution and is expressed as:

$$\varepsilon_i(\Delta z) = \frac{\varepsilon_0}{\Delta z}\mathcal{P}_i\left(\frac{\Delta z}{L_\varepsilon}\right)$$

where Δz is vertical grid spacing, ε_0 is fractional entrainment rate per event and is set to 0.2, $\mathcal{P}_i$ is a sample from the Poisson distribution, and L_ε is a length scale that can be prescribed (as in this study) or diagnosed from the environment.

Simulations

- We simulate two cases of shallow cumulus with SCAM6 and a reference LES (Matheou & Chung 2014):
  - BOMEX (Siebesma et al. 2003)
  - ARM (Brown et al. 2002)
- SCAM is run with 256 vertical levels and a 100 s timestep. Radiation, deep convection, and gravity waves are deactivated. Precipitation is minimized by setting aerosol number absurdly high
- LES is run with a 20 m isotropic grid on a 10.24 km horizontal domain

Related Presentations:

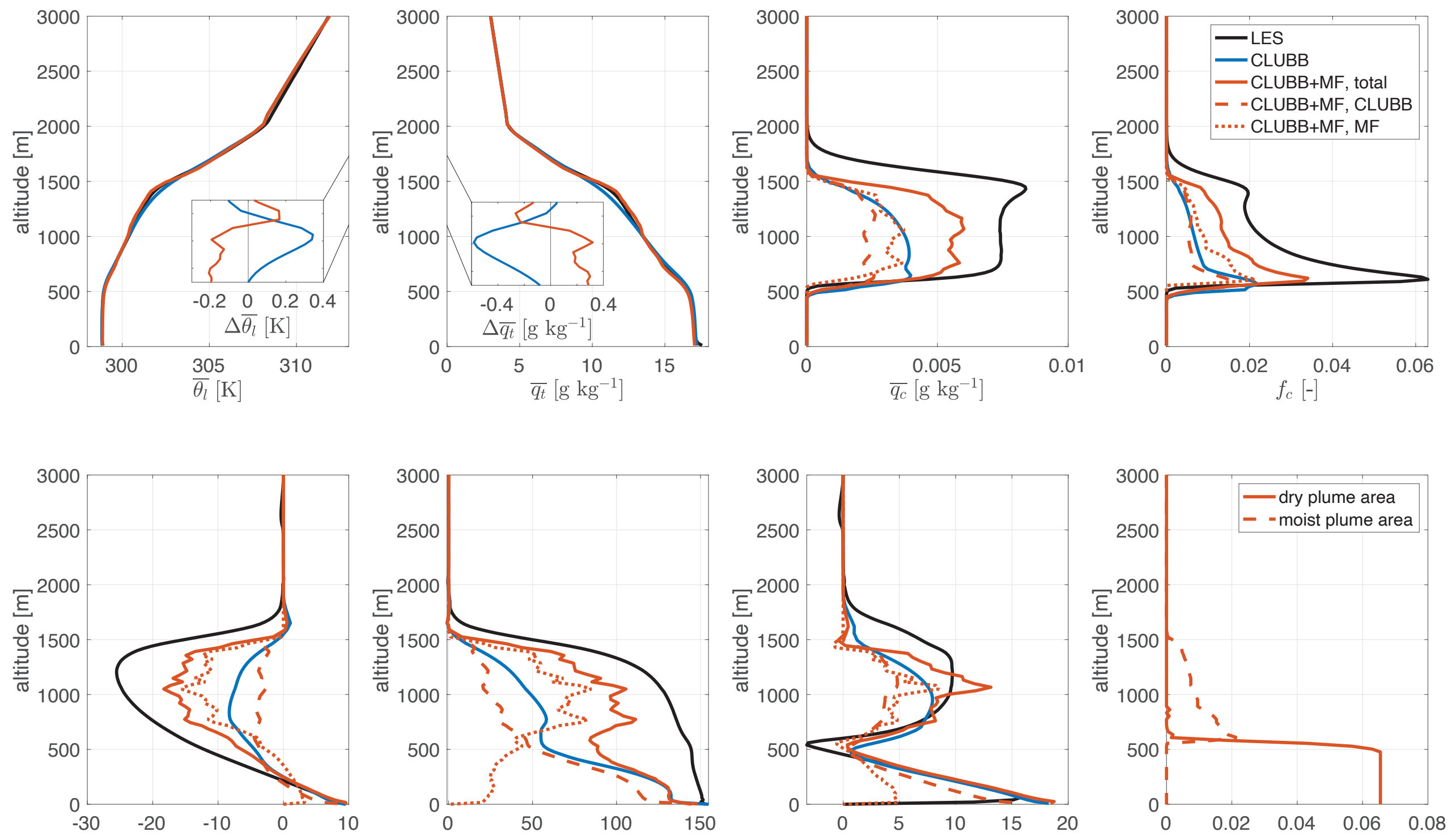
Talk (Mon) – Unified Boundary Layer and Convection Parameterizations in Global Models – Joao Teixeira
CL16 – How can weather reanalyses contribute to atmospheric model parameterization development and validation? – Mark Smalley
CL33 – Progress toward including deep convection in a unified representation of turbulence – Rachel Storer
CO67 – Improving shallow convection in the DOE SCREAM model with the Stochastic Moist Multi-Plume MF parameterization – Maria Chinita

Takeaway: Merging higher order closure and mass-flux in a unified framework improves shallow cumulus representation in SCAM6 and shows promise as a fully unified subgrid turbulence/convection scheme.

For more details, see Witte et al. (2022) in MWR:

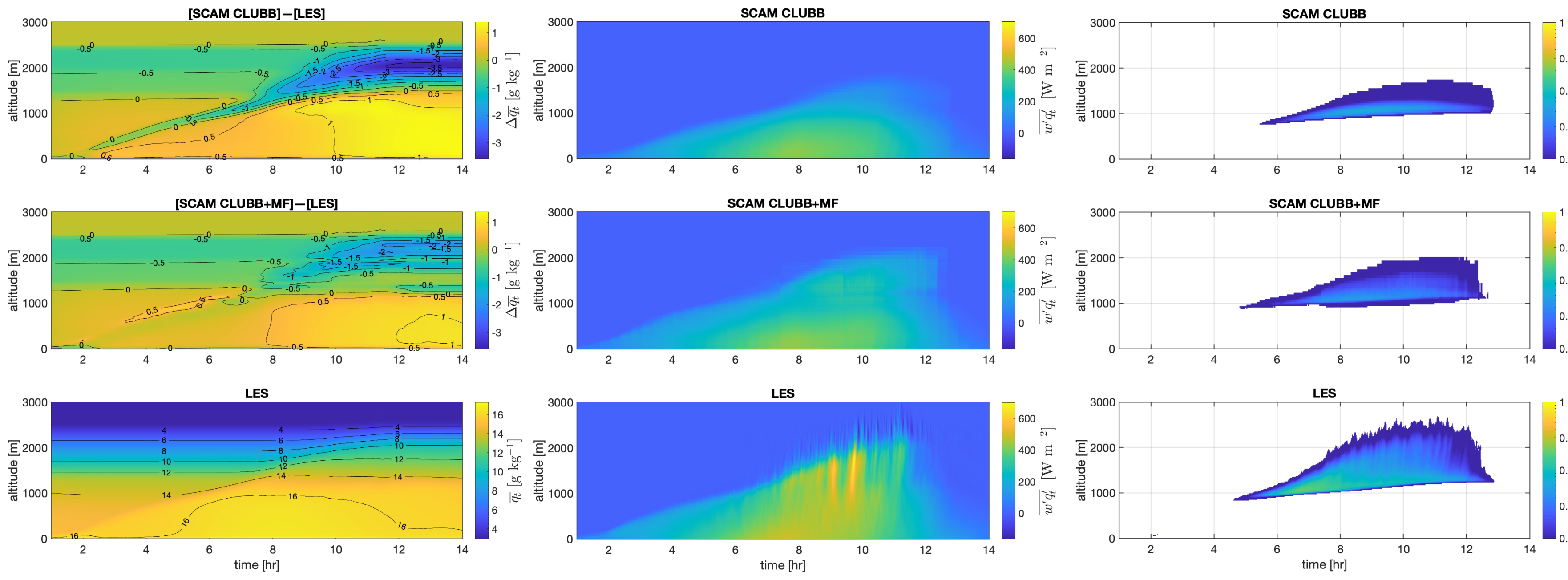
Results: steady-state marine shallow convection

The well-characterized BOMEX case features a slowly evolving non-precipitating shallow cumulus field with low cloud fraction and vertical extent of just over 1 km. Transport by coherent updrafts dominates the fluxes above the mixed layer (z~500 m). On its own, CLUBB underpredicts flux magnitudes in cloud and steeper thermodynamic gradients in the conditionally unstable layer. The result is lower cloud cover and less condensate. In comparison, CLUBB+MF has stronger fluxes and better agreement of cloud properties with reference LES.

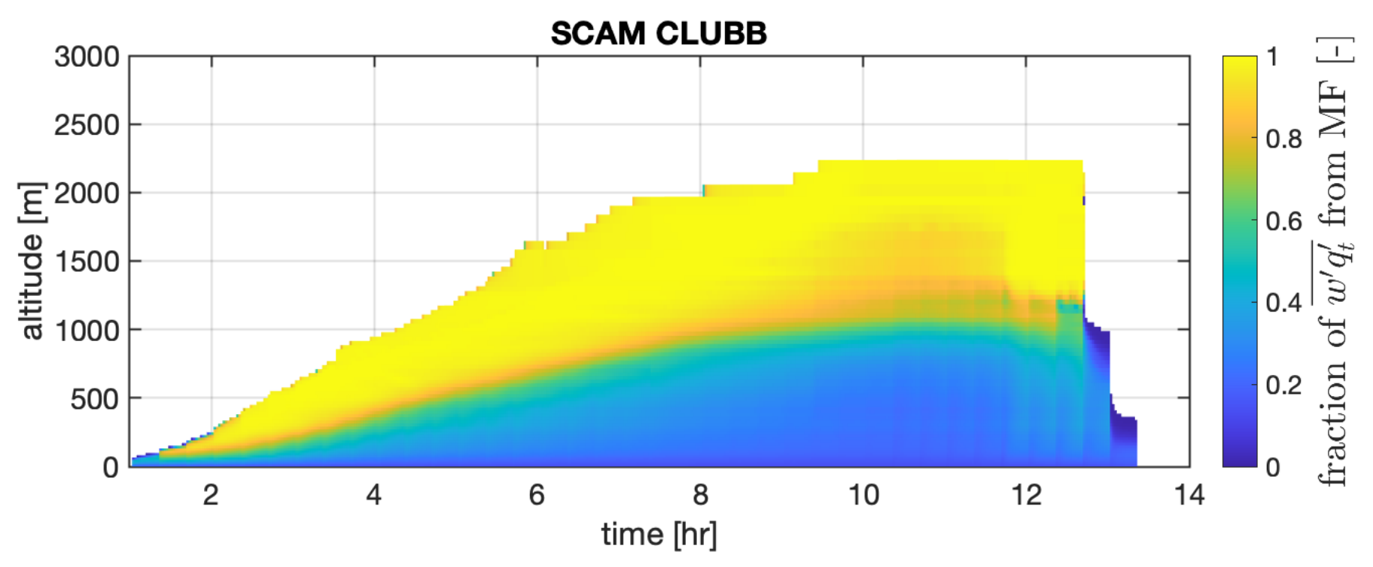


Results: diurnal cycle of continental shallow cumulus

The ARM shallow cumulus case simulates an early summer day of non-precipitating shallow cumulus over Oklahoma, evolving from a nocturnal stable layer to a dry convective boundary layer in the monring, and peaking in shallow cumulus convection in the afternoon. Here, we test the ability of CLUBB and CLUBB+MF to quickly respond to surface forcing and mix PBL air into the overlying stable layer. Compared to LES, CLUBB+MF produces a lower ql, higher qt layer from 1500-2500 m during the period of peak convection (10-12 h) and therefore deeper cloud cover. This happens because of stronger turbulent fluxes (moisture shown below).

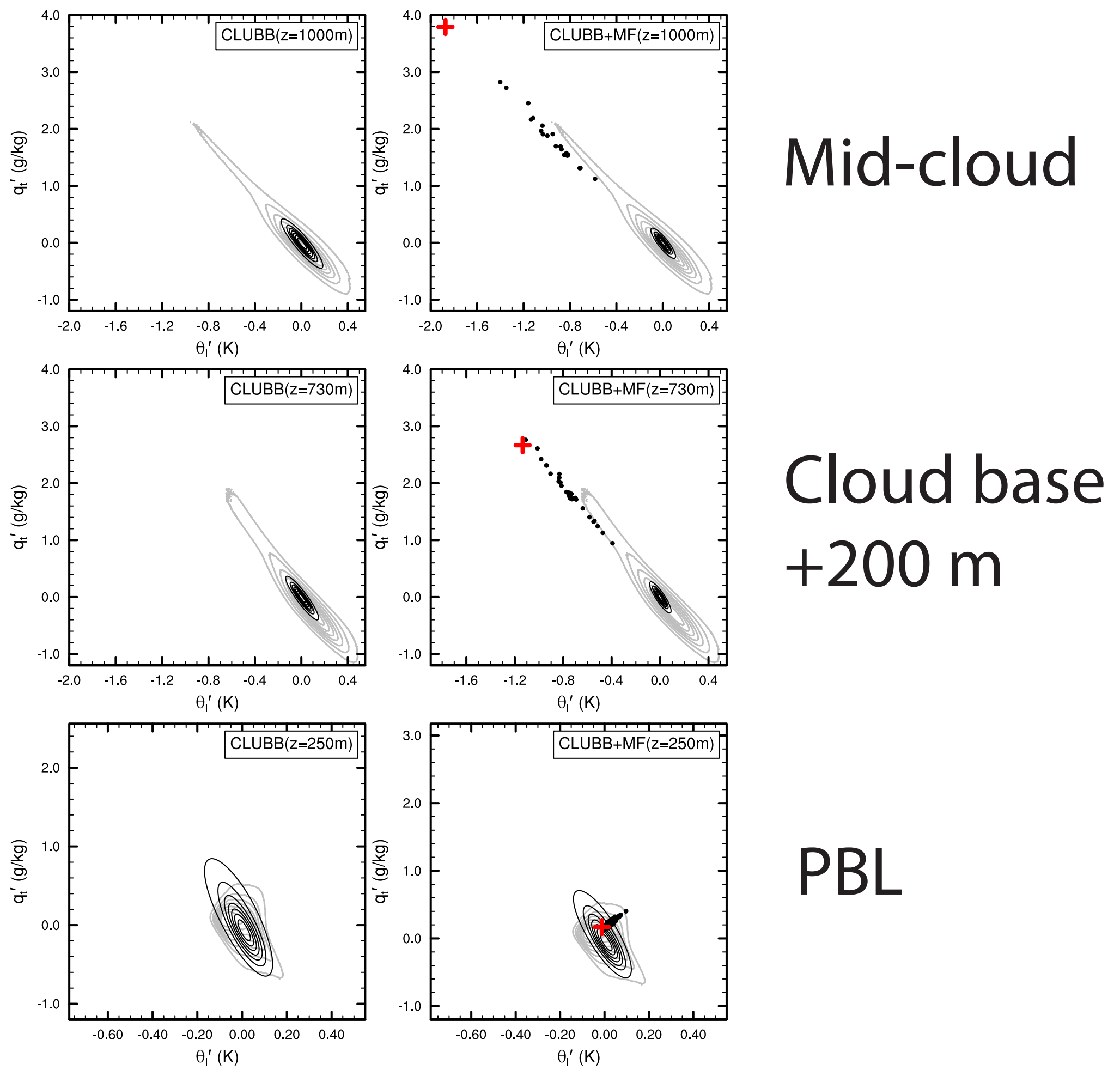


The increase in magnitude and depth of the moisture flux in the CLUBB+MF simulation is entirely due to the MF scheme. This also demonstrates the compensation that occurs between the two transport mechanisms: where once CLUBB had some contribution, MF has effectively cut off the source terms in the budget for CLUBB's prognostic fluxes.



Complementary roles of CLUBB and MF

Assumed PDF and multi-plume MF schemes are well-suited to characterizing atmospheric variability. The assumed PDF represents the centroid and lower order moments of the joint distribution of vertical velocity, temperature and moisture, while the plumes are designed to simulate the extreme tails of that distribution. The figure below demonstrates this at 3 levels during the BOMEX simulation:

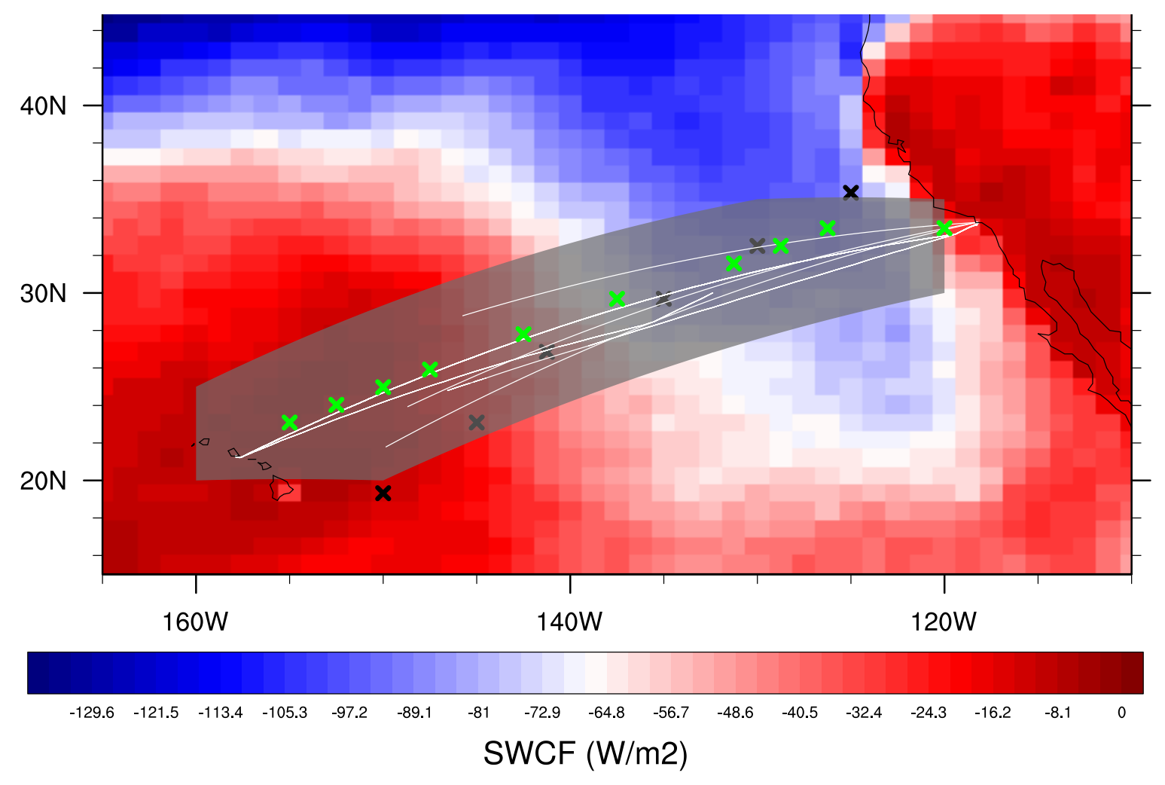


In the sub-cloud layer when updrafts have yet to entrain much, they are warmer and moister than the PBL. They cool and begin to condense as they rise while retaining much of their initial moisture (red crosses show surface conditions). The plumes gradually equilibrate with the environment as they ascend and continue to mix by entrainment. The LES shows similar covariance between the central distribution and the long tail due to convection.

Ongoing work: improving the dependence of entrainment on environment

As we transition to operating CLUBB+MF in 3D and evaluate our ability to simulate deeper convection (see poster **CL33**), we are experimenting with methods of improving the responsiveness of the entrainment length scale to environmental parameters and TKE.

As a testbed, we force the model with reanalysis (see poster **CL16**) or 3D model output (i.e., from the default configuration of CAM with CLUBB and deep convection activated) at locations across the stratocumulus to cumulus transition in the Northeast Pacific (green crosses below).



Using simple physical arguments (i.e., that small-scale turbulence should modulate plume entrainment rate), we demonstrate improvement in simulating shortwave cloud radiative effects using CLUBB+MF.