Improving shallow convection in the DOE SCREAM model with the Stochastic Moist Multi-Plume Mass-Flux parameterization

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1. Introduction and Objectives

In general circulation models (GCMs), subgrid-scale processes need to be parameterized (e.g., turbulence, convection, cloud macrophysics and microphysics, radiation, and aerosols). Turbulence, convection and cloud macrophysics are often parameterized in a modular way, which increases uncertainties and biases in climate projections.

Cloud-resolving models such as the Simple Cloud-Resolving E3SM Atmosphere model (SCREAM), with a target global resolution of 3.25 km, aim to reduce climate sensitivity uncertainty associated with parameterized convection by explicitly resolving some deep convection. In SCREAM, turbulence and shallow convection are parameterized with the TKE-based Simplified Higher-Order Closure (SHOC)—a simplified version of the assumed doubled-Gaussian PDF method combined with a 1.5-order turbulence closure (Bogenschutz and Krueger 2013). However, recent studies (Witte et al. 2022 and references within) have shown that shallow cumulus convection is not properly represented by PDF schemes due to limitations of the assumed PDF in representing high skewness and kurtosis of the distributions.

Our objective is to improve the shallow cumulus convection representation in SCREAM by merging SHOC with multiple stochastic Mass-Flux (MF) plumes, thereby creating a **unified SHOC+MF parameterization**.

2. EDMF approach

In weather and climate models, the prognostic equation of the thermodynamic variables: $\frac{\partial\bar{\phi}}{\partial t} = -\frac{\partial\overline{w'\phi'}}{\partial z} + F_\phi$.
In convective conditions, turbulence organizes into large-scale coherent structures, so $\overline{w'\phi'}$ can be decomposed into local turbulent mixing and strong organized updrafts:

$$\overline{w'\phi'} = a_e\overline{w'\phi'} + \underbrace{a_e(w_e-\bar{w})(\phi_e-\bar{\phi})}_{a_u\ll 1\rightarrow w_e\approx\bar{w}\approx 0} + \underbrace{a_u\overline{w'\phi'}_u}_{updrafts\ horiz.\ homogeneous} + a_u(w_u-\bar{w})(\phi_u-\bar{\phi})$$

In the multi-plume Eddy-Diffusivity Mass-Flux (EDMF) approach:

$$\overline{w'\phi'} = -K_\phi\frac{\partial\bar{\phi}}{\partial z} + \sum_{n=1}^{N} M_n(\phi_n-\bar{\phi})$$

where $M_n = a_n w_n$ is the *n*th-plume mass-flux contribution.

3. SHOC+MF parameterization

In SHOC, the second-order moments needed to construct the PDF are diagnosed for computational efficiency. Accordingly, the heat and moisture turbulent fluxes are estimated following an eddy-diffusivity approach: $\overline{w'\phi'} = -K_\phi\frac{\partial\bar{\phi}}{\partial z}$, where $\phi = \{\theta_l, q_t\}$, and K_ϕ represents the heat eddy-diffusivity coefficient.

We base our MF scheme on the stochastic multi-plume EDMF approach of Suselj et al. (2019), in which *N* independent and steady-state plumes are initiated at the surface, and their vertical evolution depends on the surface properties and stochastic-based lateral entrainment.

We implement the stochastic MF scheme in SCREAM by coupling it to SHOC. Thus, the multi-plume MF contribution is added to SHOC's numerical solver for the mean thermodynamic variables $\phi = \{\theta_l, q_t\}$:

$$\frac{\partial\bar{\phi}}{\partial t} = -\frac{\partial\overline{w'\phi'}}{\partial z} = -\frac{\partial}{\partial z}\left(\underbrace{-K_\phi\frac{\partial\bar{\phi}}{\partial z}}_{SHOC} + \underbrace{\sum_{n=1}^{N} a_n(w_n-\bar{w})(\phi_n-\bar{\phi})}_{multi-plume\ MF}\right)$$

In our framework, SHOC represents the local mixing and MF the strong nonlocal mixing.

4. Single-column model simulations

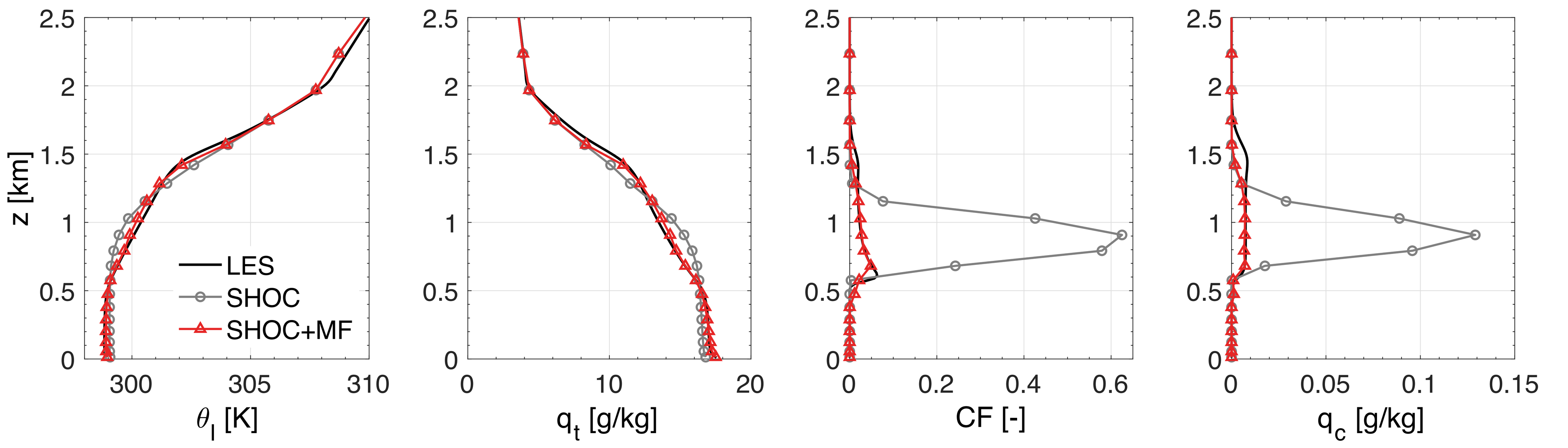
Two benchmark cases are explored to assess the SHOC+MF ability to represent shallow cumulus convection using SCREAM in a single-column model (SCM) framework. We evaluate our SHOC+MF parameterization against large-eddy simulation (LES) reference data (Matheou and Chung, 2014). The microphysics and radiation schemes are off for a more direct comparison with the LES data. In our SCM simulations, we used a 72-layer vertical grid, the dynamic and physics timesteps are equal to 30 minutes and 5 minutes, respectively, and the surface turbulent fluxes are prescribed. Lastly, we used 50 plumes.

Related Presentations

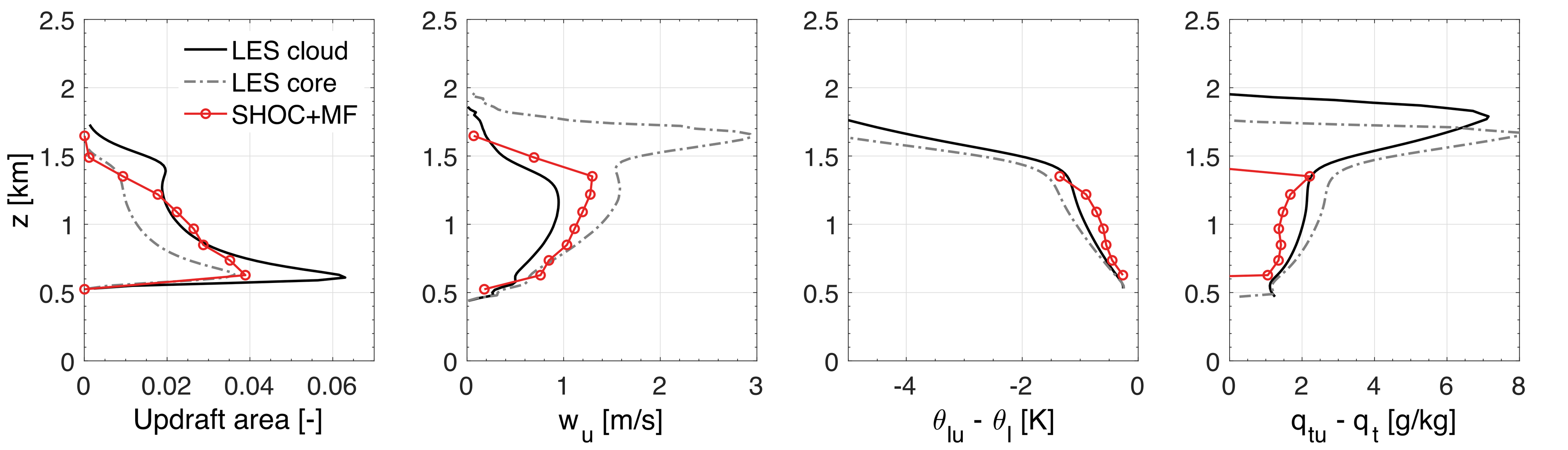
Talk Unified Boundary Layer and Convection Parameterizations in Global Models by Joao Teixeira.
CL08 Augmenting the double-Gaussian representation of atmospheric turbulence and convection via a coupled stochastic multi-plume mass flux scheme by Mikael Witte.
CL33 Progress toward including deep convection in a unified representation of turbulence by Rachel Storer.
CL16 How can weather reanalyses contribute to atmospheric model parameterization development and validation? by Mark Smalley.

5. BOMEX

Mean profiles of the shallow cumulus BOMEX case (Siebesma et al., 2003)—quasi-steady-state warm maritime shallow convection over the Atlantic ocean, averaged over *t* = 4–6 h.



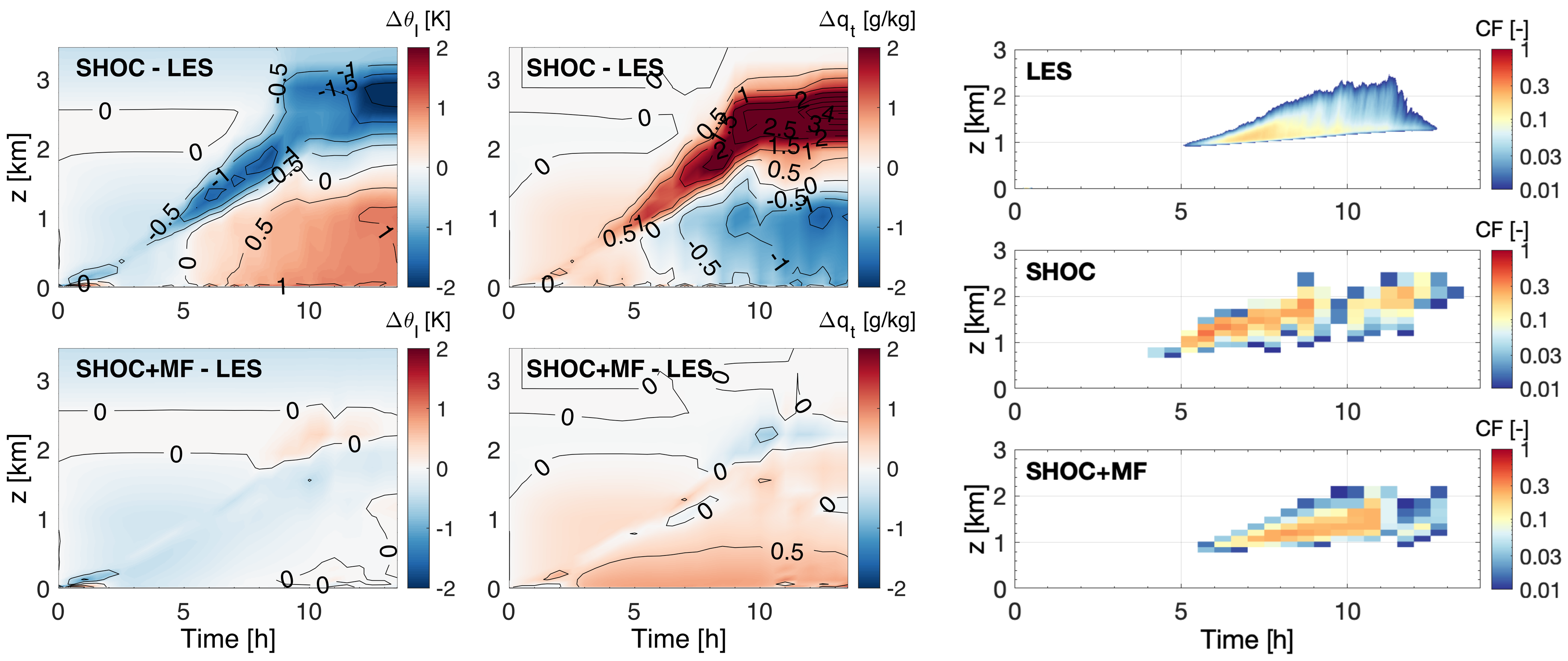
SHOC+MF improves the vertical distribution of liquid water potential temperature, water vapor, and cloud macrophysics properties while SHOC: (i) does not reproduce a shallow cumulus layer, (ii) does not produce a deep enough PBL, and (iii) overestimates the cloud macrophysics properties.



The SHOC+MF moist updraft properties agree well with the LES confirming the physical behavior of the SHOC+MF scheme.

6. ARM shallow convection

Diurnal evolution of temperature and moisture differences relative to the LES fields (left) and cloud fraction (right) for the ARM shallow cumulus case (Brown et al. 2002)—diurnal cycle of warm shallow convection over land at the Southern Great Plains site of the Atmospheric Radiation Measurement (ARM) program.



The SHOC+MF scheme improves the diurnal evolution of the thermodynamic variables and cloud fraction.

References

Bogenschutz, P. A., and S. K. Krueger, 2013: A simplified PDF parameterization of subgrid-scale clouds and turbulence for cloud-resolving models. *JAMES*, **5**, 195–211.
Brown, A. R., and Coauthors, 2002: Large-eddy simulation of the diurnal cycle of shallow cumulus convection over land. *QJRMS*, **128**, 1075–1093.
Matheou, G., and D. Chung, 2014: Large-eddy simulation of stratified turbulence. Part II: Application of the stretched-vortex model to the atmospheric boundary layer. *JAS*, **71**, 4439–4460.
Siebesma, A., and Coauthors, 2003: A large eddy simulation intercomparison study of shallow cumulus convection. *JAS*, **60**, 1201–1219.
Suselj, K., M. J. Kurowski, and J. Teixeira, 2019: A unified eddy-diffusivity/mass-flux approach for modeling atmospheric convection. *JAS*, **76**, 2505–2537.
Witte, M. K., and Coauthors, 2022: Augmenting the double-Gaussian representation of atmospheric turbulence and convection via a coupled stochastic multi-plume mass flux scheme. *MWR, in press.*

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