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Unified Parameterizations of Boundary Layer Turbulence and Convection in Global Atmospheric Models

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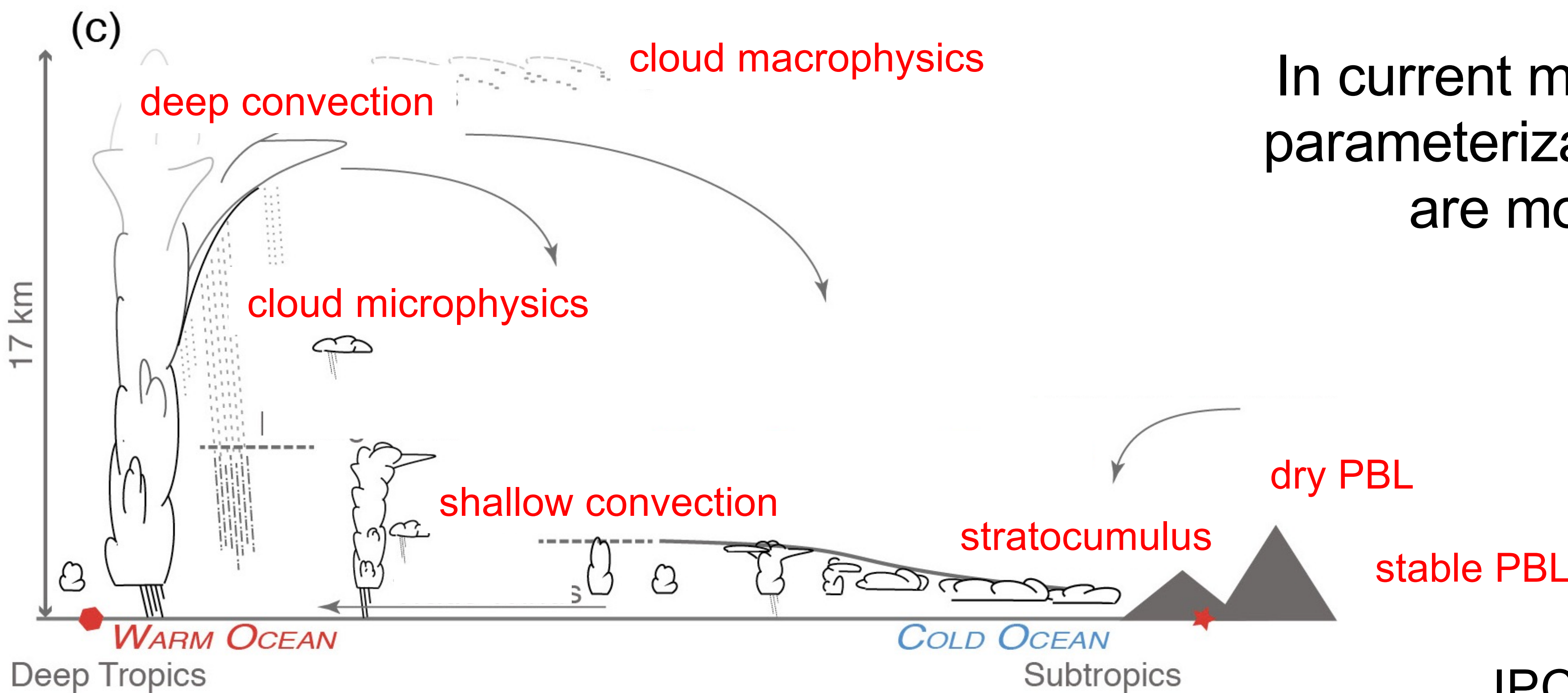
Turbulence, Convection and Cloud Parameterizations

The atmosphere is a turbulent fluid where mixed-phase physics and radiative transfer play an essential role



In current models parameterizations are modular

IPCC AR5

Goal: Unified parameterization for turbulence, clouds and convection

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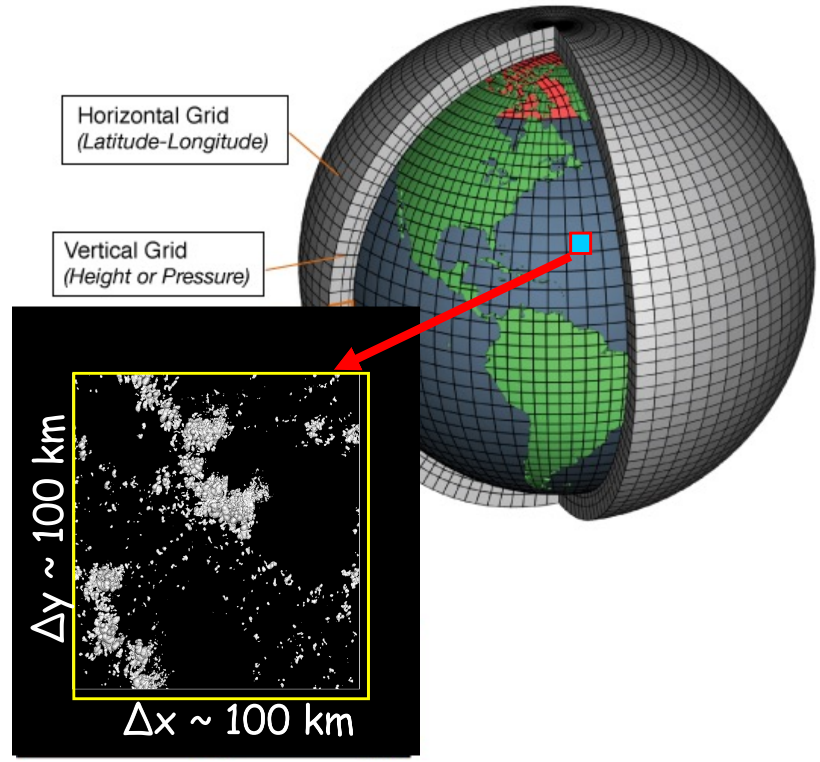
Global Atmospheric Models



3D Atmospheric Models:

3D Large-scale dynamics +
One-dimensional physics

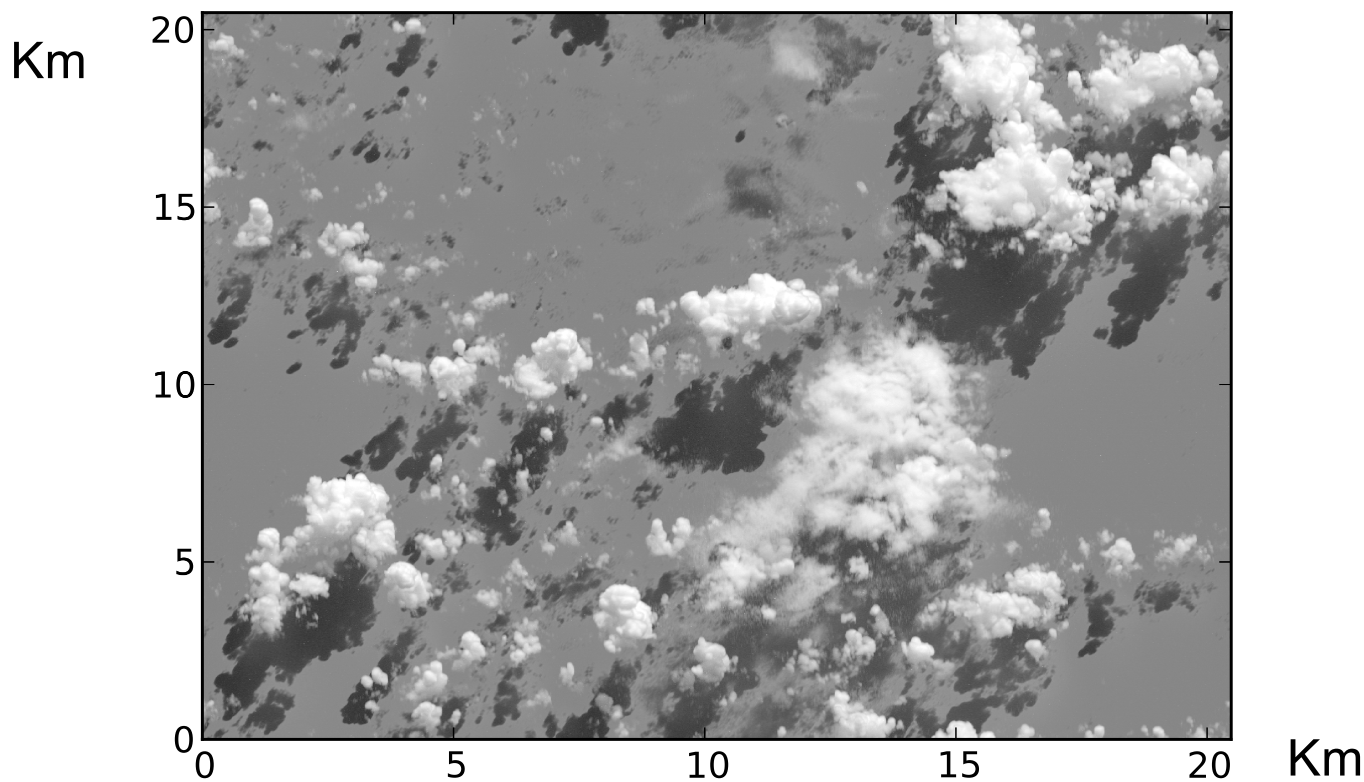
Reynolds decomposition and averaging:

$$\varphi = \overline{\varphi} + \varphi' \quad \Rightarrow \quad \frac{\partial \overline{\varphi}}{\partial t} + \frac{\partial}{\partial x}\left(\overline{u}\,\overline{\varphi}\right) + \frac{\partial}{\partial y}\left(\overline{v}\,\overline{\varphi}\right) + \frac{\partial}{\partial z}\left(\overline{w}\,\overline{\varphi}\right) = -\frac{\partial}{\partial z}\left(\overline{w'\varphi'}\right) + \overline{S},$$

Key turbulence and convection parameterization problem

Large-Eddy Simulation (LES) models

- LES models solve filtered version of Navier-Stokes equations
- High-resolutions (~ 10 m) in all 3 dimensions
- LES models resolve most of the essential turbulence/convection
- Closures still needed for scales < 10m (but simpler than GCMs)



Matheou et al., MWR, 2011

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Merging ED and MF: Eddy-Diffusivity/Mass-Flux (EDMF)

Dividing a grid square in two regions (updraft and environment) and using Reynolds decomposition and averaging leads to

$$\overline{w'\varphi'} = a_u \overline{w'\varphi'}_u + (1-a_u)\overline{w'\varphi'}_e + a_u(1-a_u)(w_u - w_e)(\varphi_u - \varphi_e)$$

where a_u is the updraft area. Assuming $a_u \ll 1$ and $w_e \sim 0$ leads to

$$\overline{w'\varphi'} = \overline{w'\varphi'}_e + a_u w_u (\varphi_u - \bar{\varphi})$$

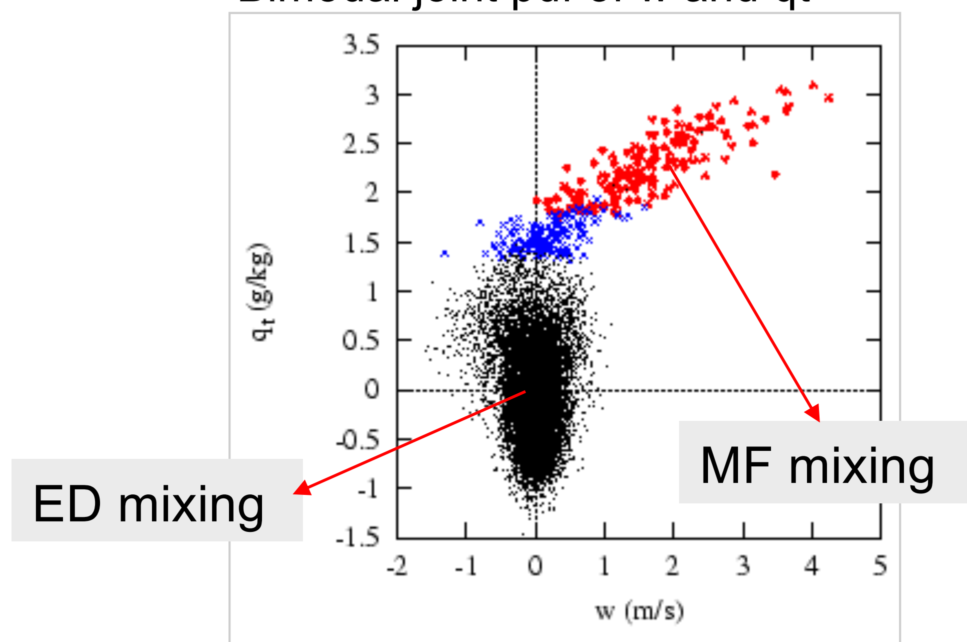
ED closure: assuming ED for 1st term and neglecting 2nd term

MF closure: neglecting 1st term and assuming $M = a_u w_u$

EDMF: $$\overline{w'\varphi'} = -k\frac{\partial\bar{\varphi}}{\partial z} + M(\varphi_u - \bar{\varphi})$$

Siebesma & Teixeira, 2000

Bimodal joint pdf of w and qt



Unified parameterization of different turbulence and convection scales

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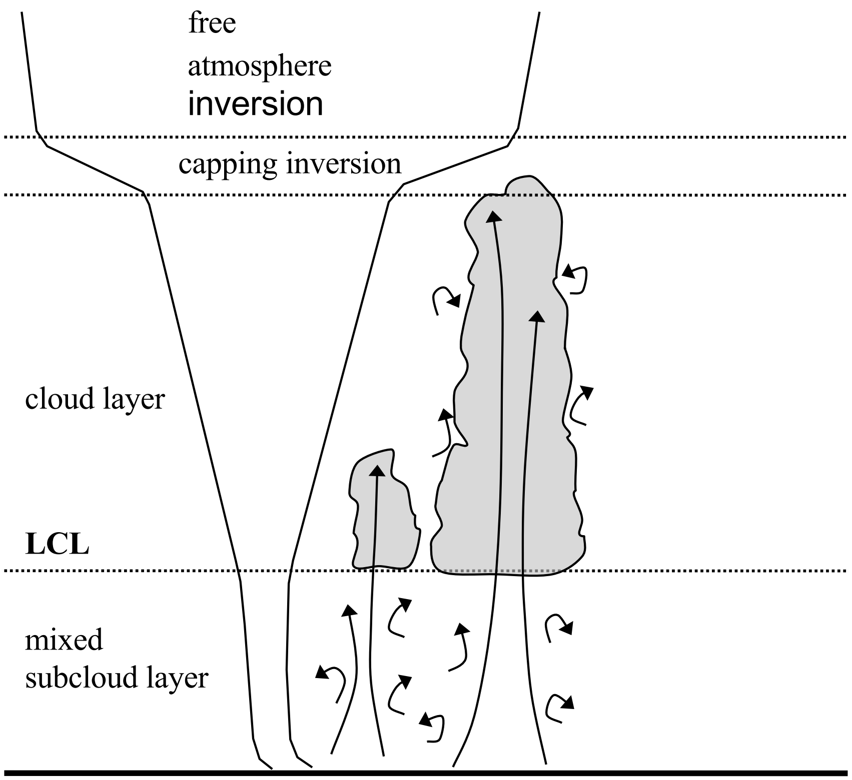
Mass-Flux Model for Plumes/Updrafts

Mass-Flux (MF) approximation leads to (in simplified form):

$$\overline{w'\theta'} = M(\theta_u - \bar{\theta})$$



1) Integrating over plume area
2) Assuming steady-state
3) Neglecting some sources/sinks

$$\frac{\partial \phi_u}{\partial z} = -\varepsilon(\phi_u - \bar{\phi}) \text{ for } \phi \in \{\theta_l, q_t\}$$

$$M = \sigma_u w_u$$

$$\frac{1}{2}\frac{\partial w_u^2}{\partial z} = -b\varepsilon w_u^2 + a\frac{g}{\theta_0}\left(\theta_{v,u} - \overline{\theta_v}\right)$$

σ_u is updraft/plume area fraction

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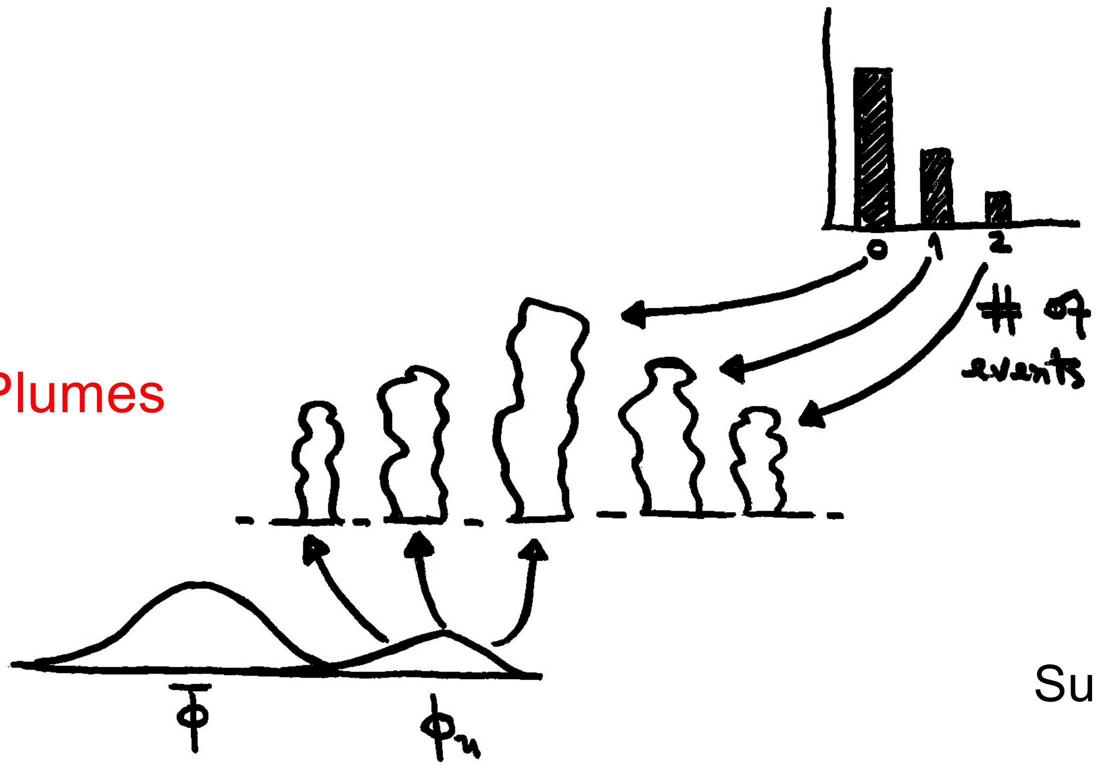
Moist convection: EDMF multiple plumes and stochastic entrainment

3) Stochastic
lateral entrainment

Partly inspired by
Romps & Kuang,
JAS, 2010

Multiple Plumes



Suselj et al., JAS, 2013, 2019

1) Parameterization of surface layer PDF of thermodynamics
2) Monte Carlo sampling of PDF to produce multiple plumes

- Different types of convection coexist in the same model grid-box
- Total updraft area is just the sum of individual updraft areas

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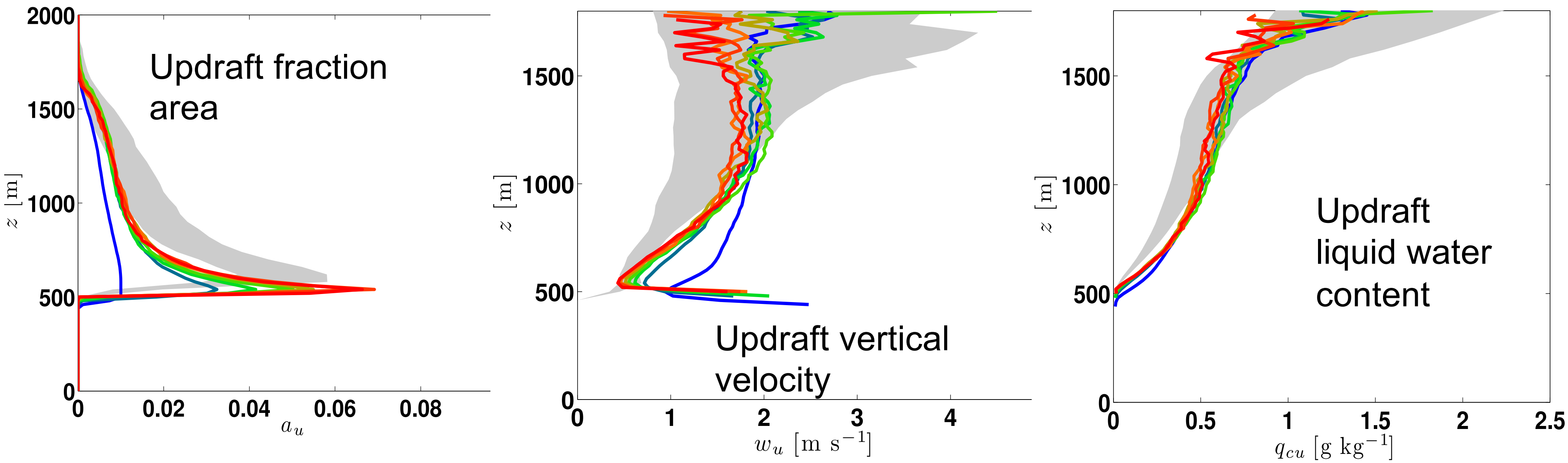
EDMF Multiple plumes: Shallow Convection

BOMEX Shallow Convection case: EDMF versus LES results



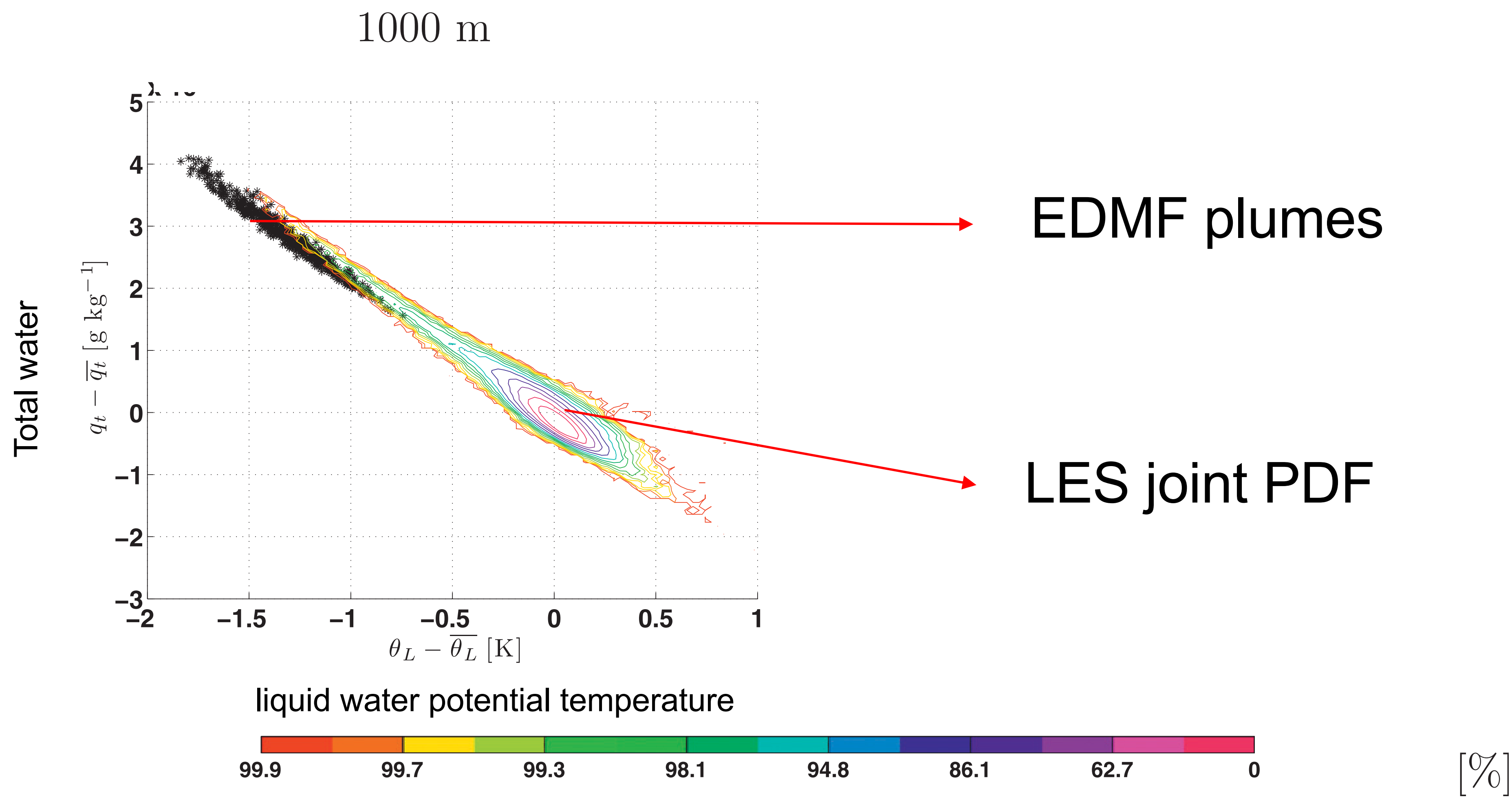
LES

EDMF colors

Suselj et al., JAS, 2013, 2019

EDMF produces realistic thermodynamics and updraft properties

BOMEX shallow convection: LES PDF vs EDMF plumes



EDMF multiple plumes represent skewed part of PDF of thermodynamic properties leading to more efficient vertical mixing

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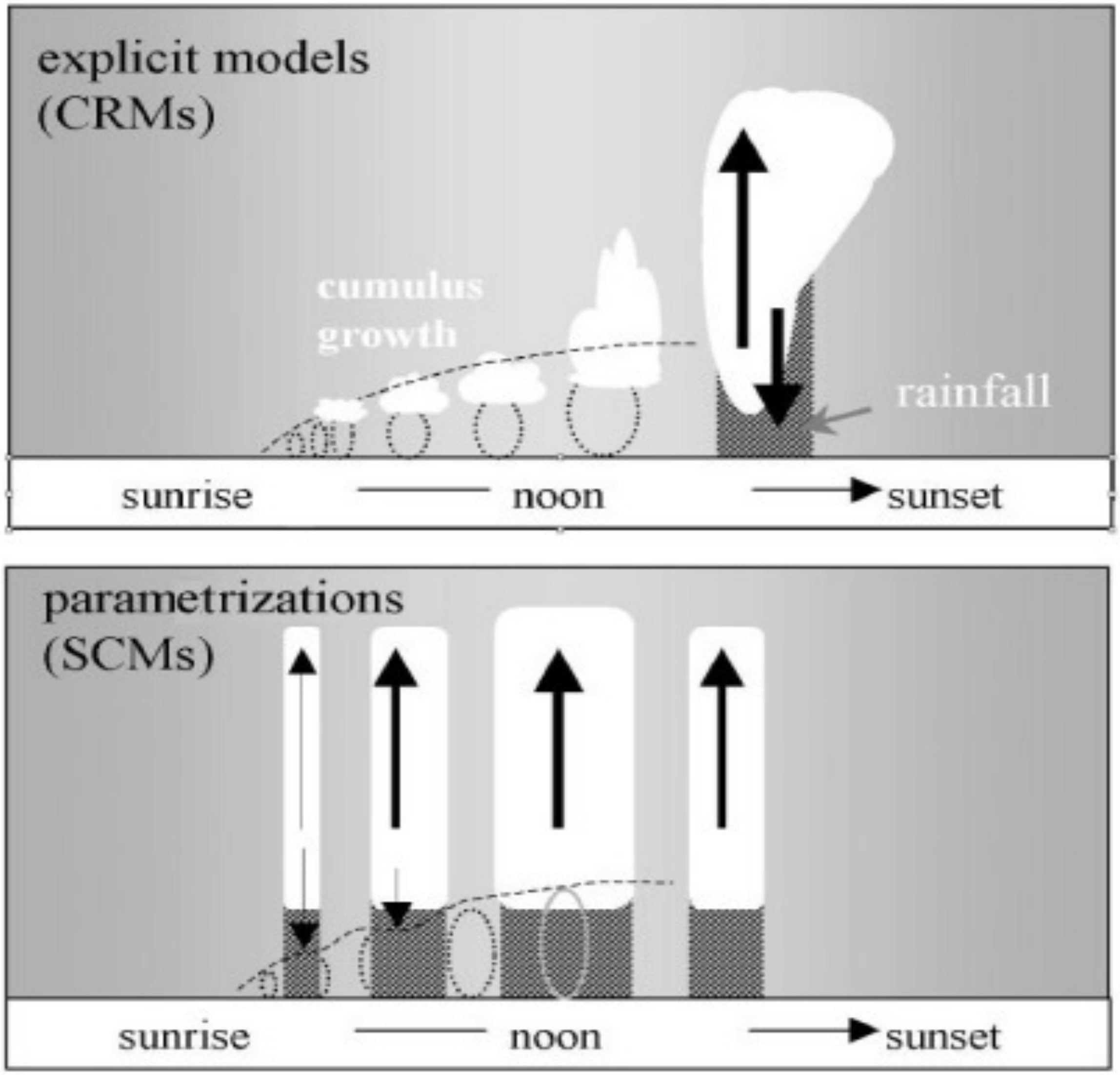
Diurnal Cycle of Convection over Land: Transition from Shallow to Deep Convection



Guichard et al., QJRMS, 2004

Climate and weather models are unrealistic

Diurnal cycle of precipitating tropical convection over land: LBA case

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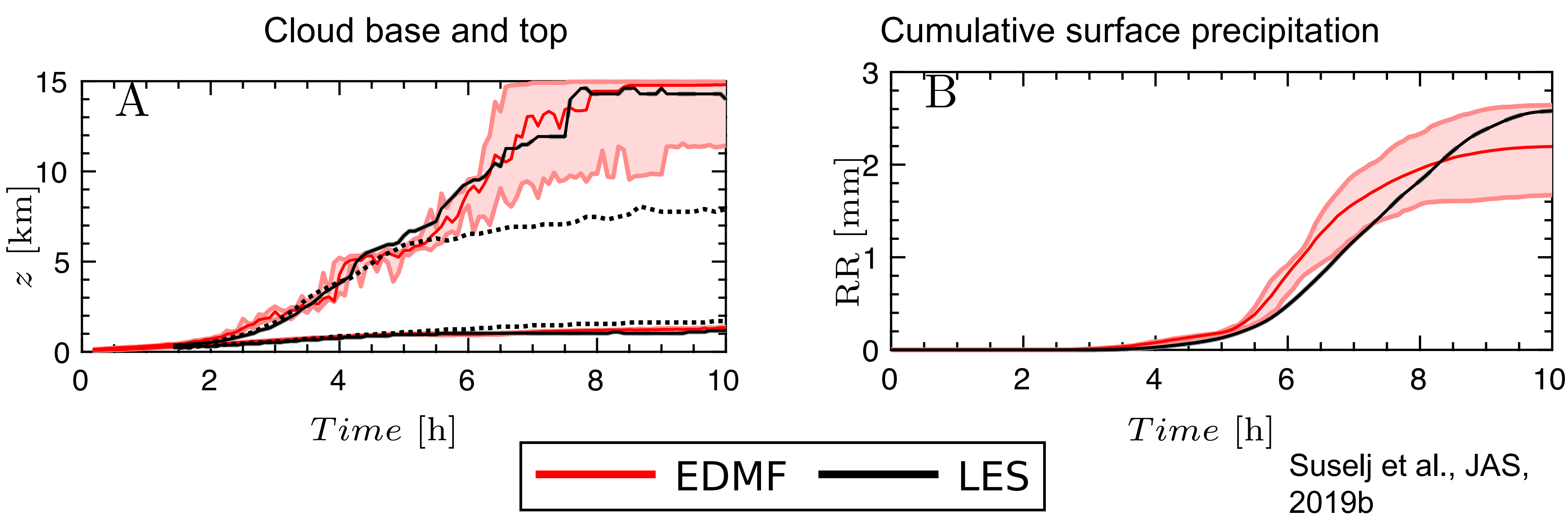
Multi-plumes with simplified parameterizations of microphysics, downdrafts and cold pool effects



Suselj et al., JAS, 2019b

Realistic transition from PBL to shallow to deep convection

A single scheme able to represent all these types of convection

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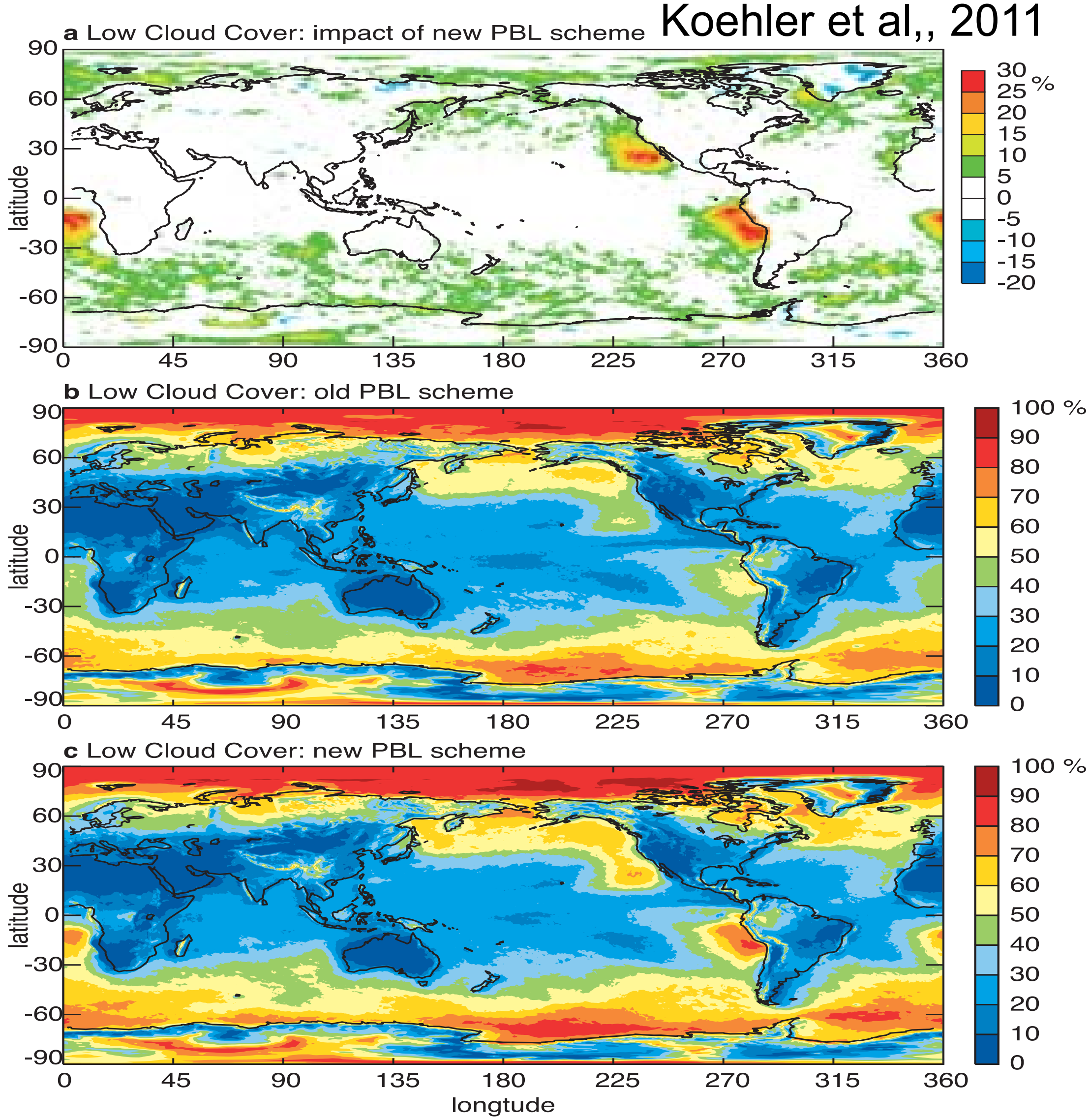
Global atmospheric models and unified parameterization approaches

Koehler et al,, 2011



EDMF has been implemented operationally in a variety of global atmospheric models: ECMWF, NCEP, US Navy

Over the last 20 years different groups have been developing unified parameterizations, including:

- Lappen & Randall (2001)
- **Golaz et al. (2002)**
- **Bogenschutz & Krueger (2013)**

Significant PBL cloud improvements in ECMWF model with EDMF

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Merging Higher-Order Closure with Multi-plume Mass-Flux: CLUBB + MF

- **CLUBB represents double-gaussian mixing while MF plumes represent additional discrete skewness of the sub-grid PDF**

- Multi-plume MF: 1) Sampling from surface layer thermodynamic PDFs; 2) Stochastic lateral entrainment based on TKE

- MF plumes are coupled to CLUBB via 5-diagonal prognostic solver for mean fields and turbulent fluxes (solved simultaneously):

$$\frac{\bar{\varphi}^{t+\Delta t}}{\Delta t} + \frac{1}{\rho_s}\frac{\partial}{\partial z}\rho_s \overline{w'\varphi'}^{t+\Delta t}_{CLUBB}$$

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

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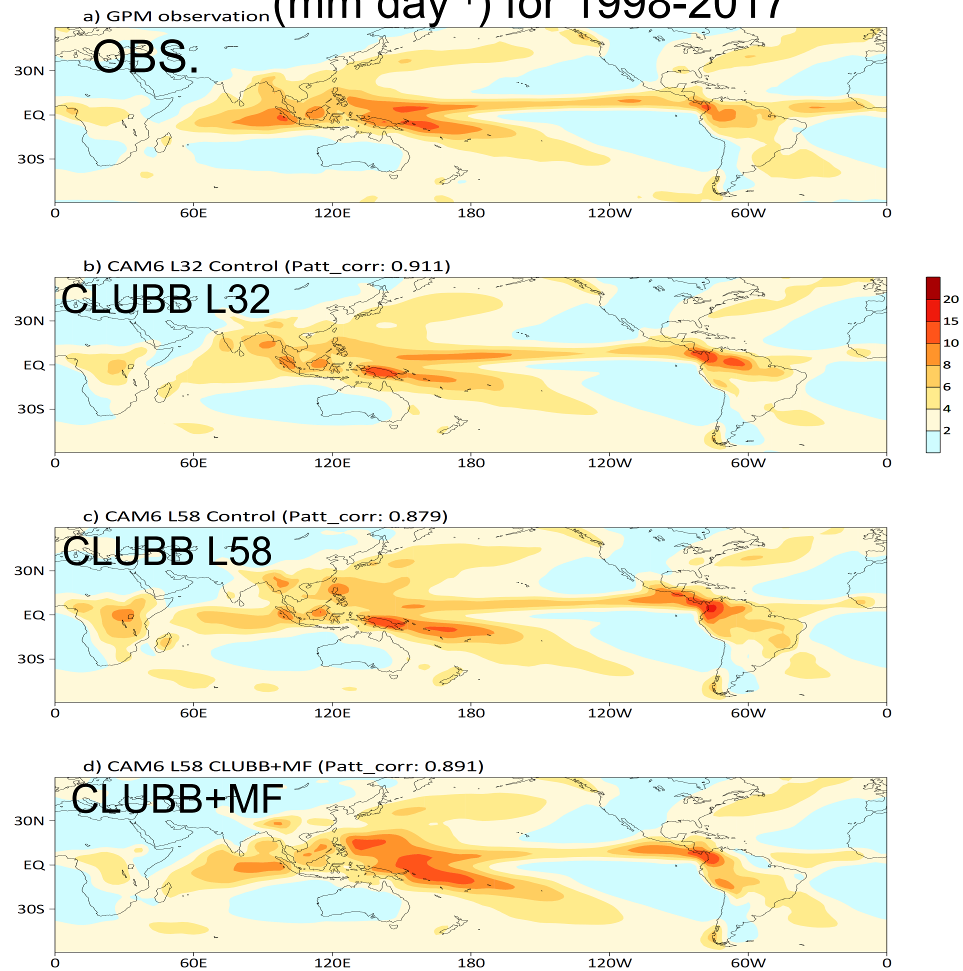
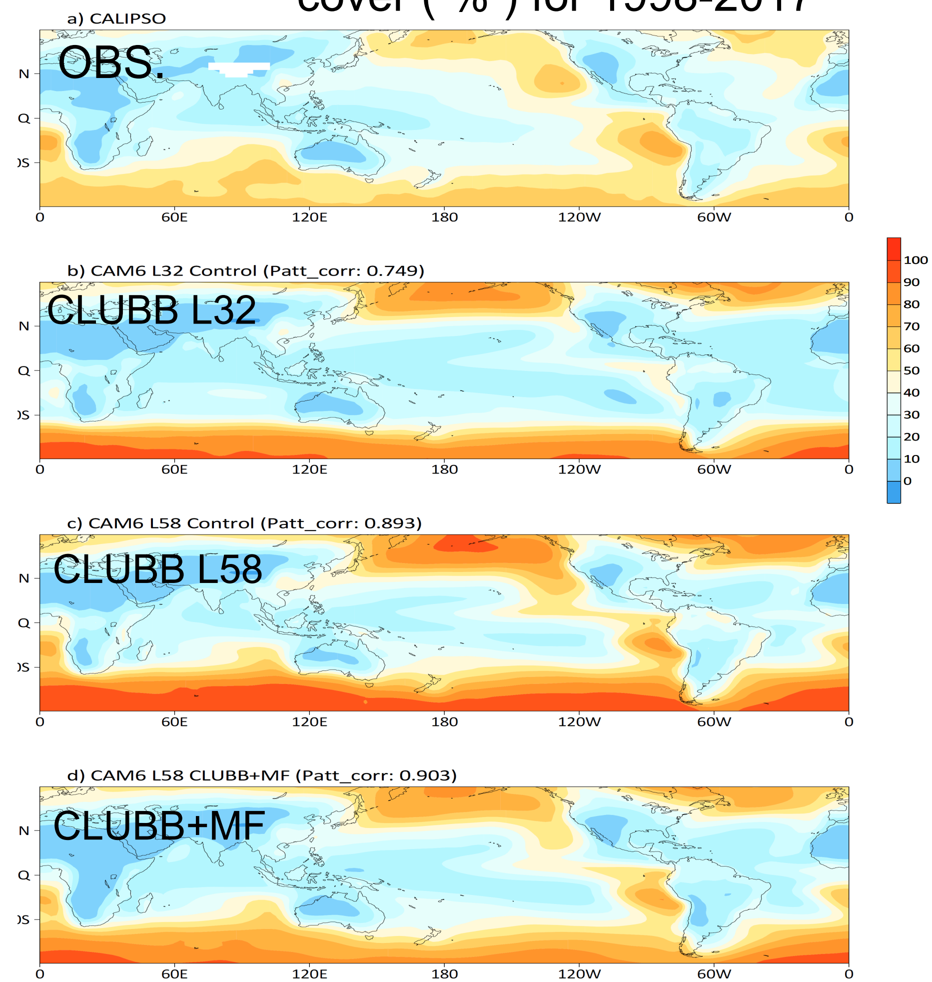
Merging higher-order closure with MF multiple plumes: PBL+ Shallow+ Deep Convection

CLUBB+MF simulations without deep convection parameterization: Realistic climatology of clouds, precipitation, TOA radiation

Annual mean precipitation (mm day^{-1}) for 1998-2017



Annual mean low-cloud cover (%) for 1998-2017

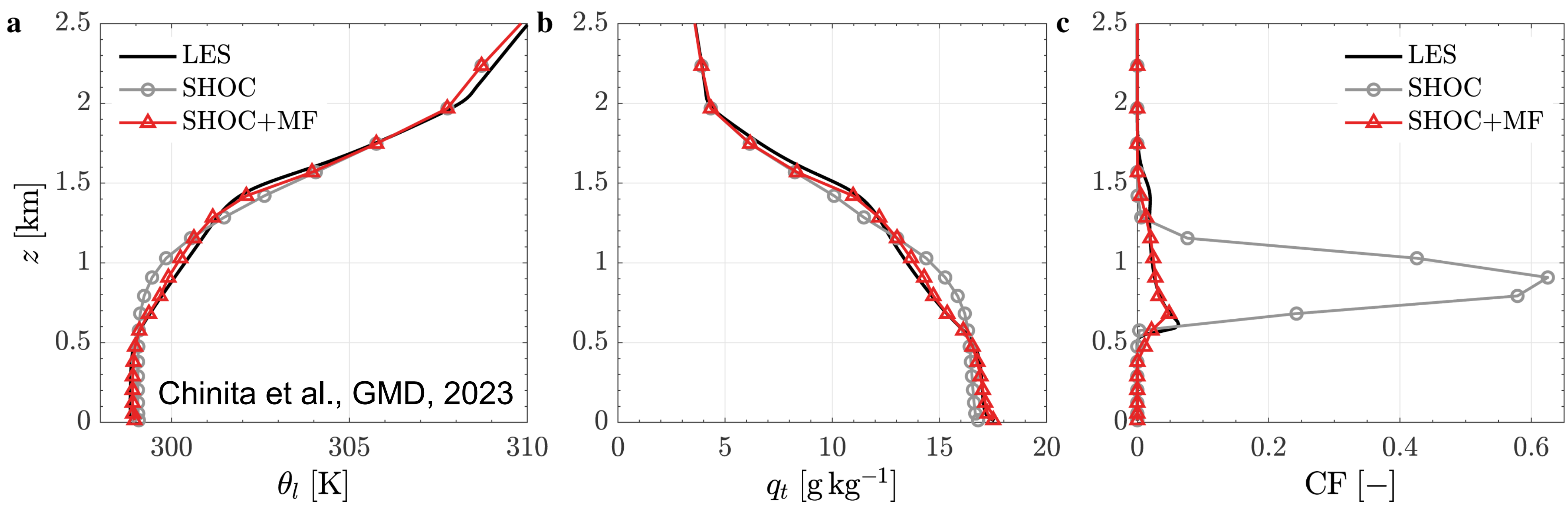


First fully unified turbulence/convection parameterization in 3D global model

SHOC+MF in the SCREAM Model

Unifying turbulence and convection by merging the Simplified Higher-Order Closure (SHOC) with multi-plume MF (SHOC+MF)

BOMEX shallow convection case (hour 4-6)



SHOC+MF produces realistic thermodynamic structure of the atmosphere in shallow moist convection regimes

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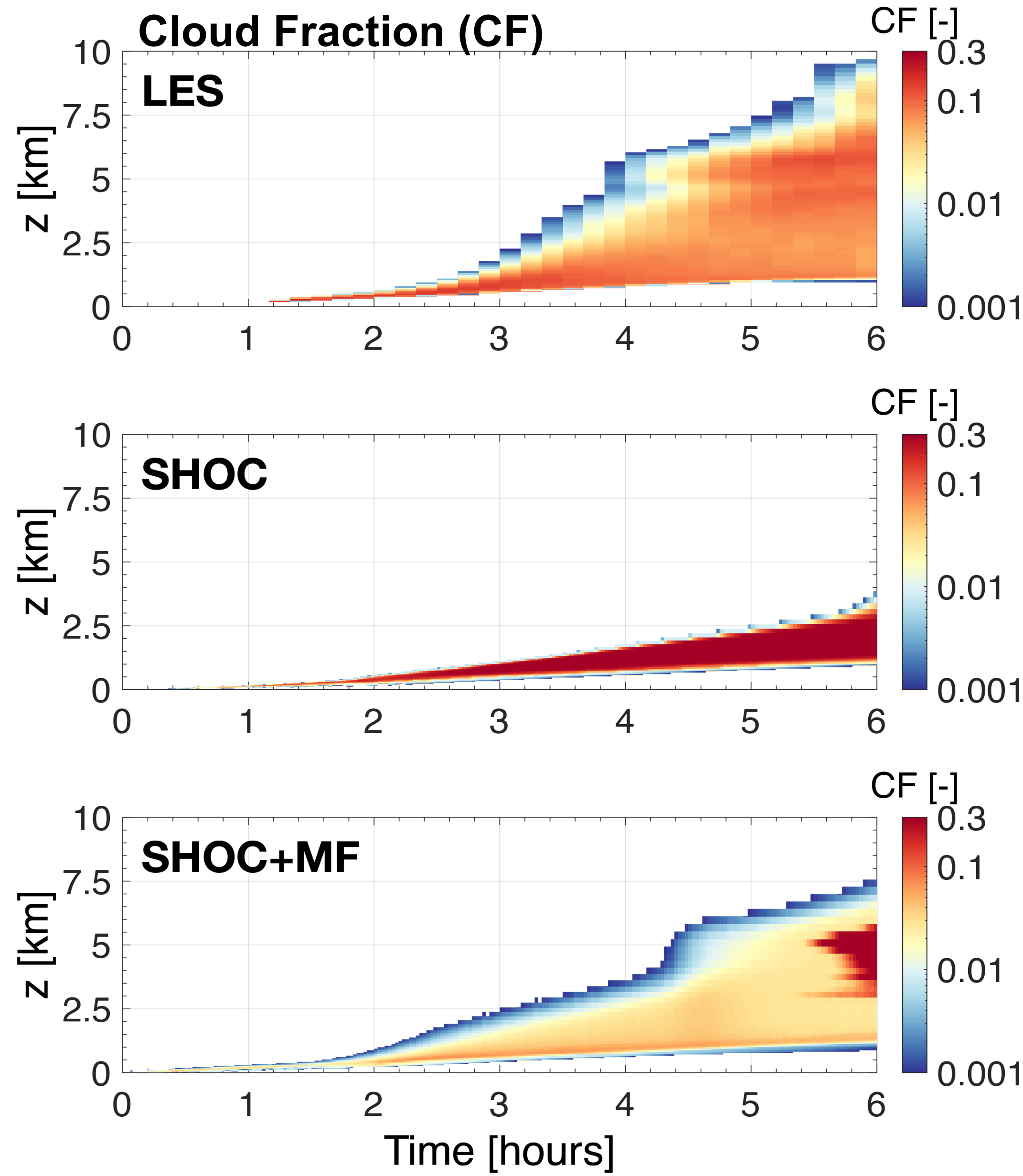
Diurnal cycle of tropical convection over land: SHOC+MF

Merging SHOC and multi-plume MF in DP-SCREAM: SHOC+MF

SHOC+MF produces realistic shallow convection
(Chinita et al., 2023)

SHOC+MF realistic transition from PBL to moist convection

A single scheme able to represent different types of convection



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Summary

- **EDMF** is a unified parameterization that blends ED approach (small-scale turbulence) with MF approach (larger eddies)

- **EDMF** represents well turbulence and convection in the global atmosphere and was implemented in global NWP models

- Fully unified parameterization of turbulence and convection (from PBL to deep convection) implemented for the first time in 3D global model: **CLUBB+MF** in CAM

- **SHOC+MF** is being tested in DOE DP-SCREAM and showing positive results for shallow and transition to deep convection