A new unified stochastic parameterization for boundary layer, shallow and deep convection

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Why a new turbulence parameterization?

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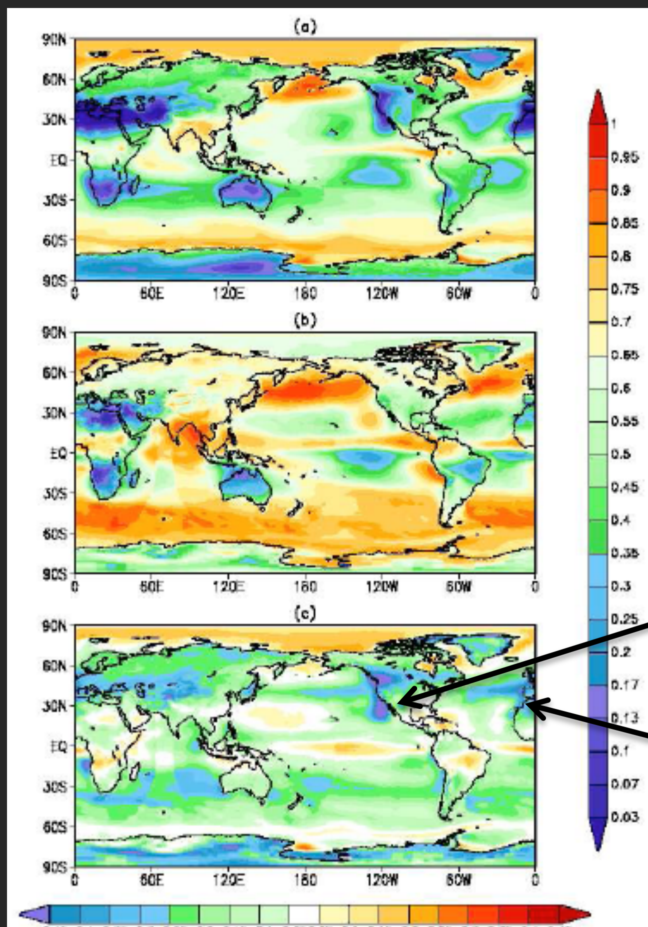
POOR REPRESENTATION OF SUBTROPICAL CLOUD TRANSITIONS

GEOS-5 model

Observations (surface radiation budget)

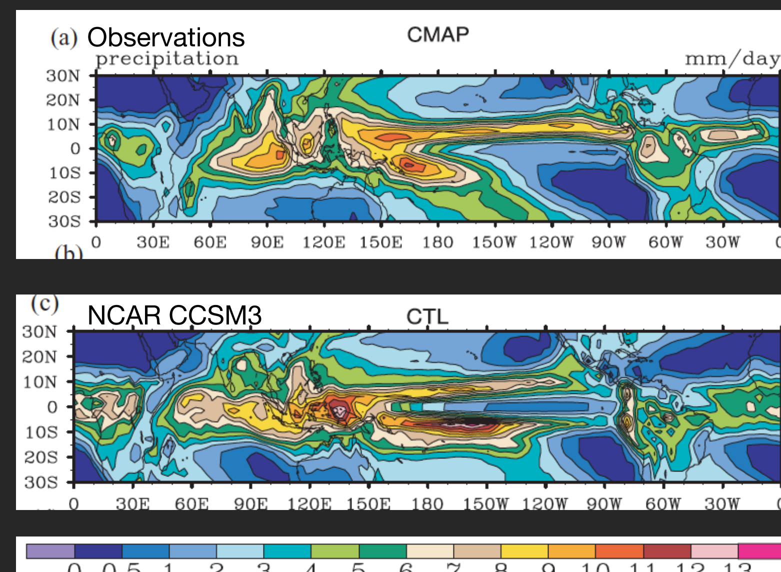
Model-Observations



DOUBLE ICTZ IN GCMS

Example from Song & Zhang (2009)

Annual precipitation

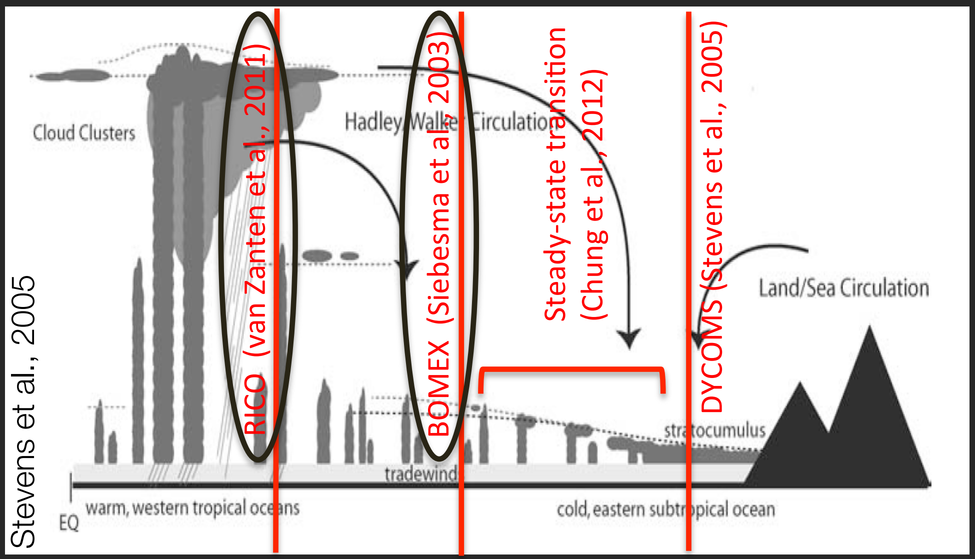


Parameterization development and validation 'test-bed'

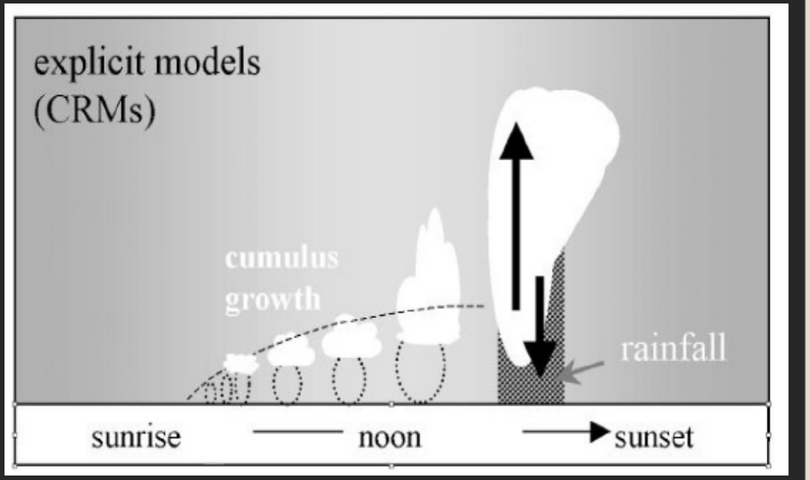
CONVECTION IN MARINE AND CONTINENTAL ENVIRONMENTS

- Development and testing of parameterization in a single-column model framework ("a vertical column of a GCM")
- Validation of benchmark cases against Large Eddy Simulations (LESs)/Cloud Resolving Models (CRMs)

Marine boundary layer



Continental convection



ARM – non-precipitating (Brown et al., 2002)

EUROCS – precipitating (Guichard et al., 2004)

Parameterization model

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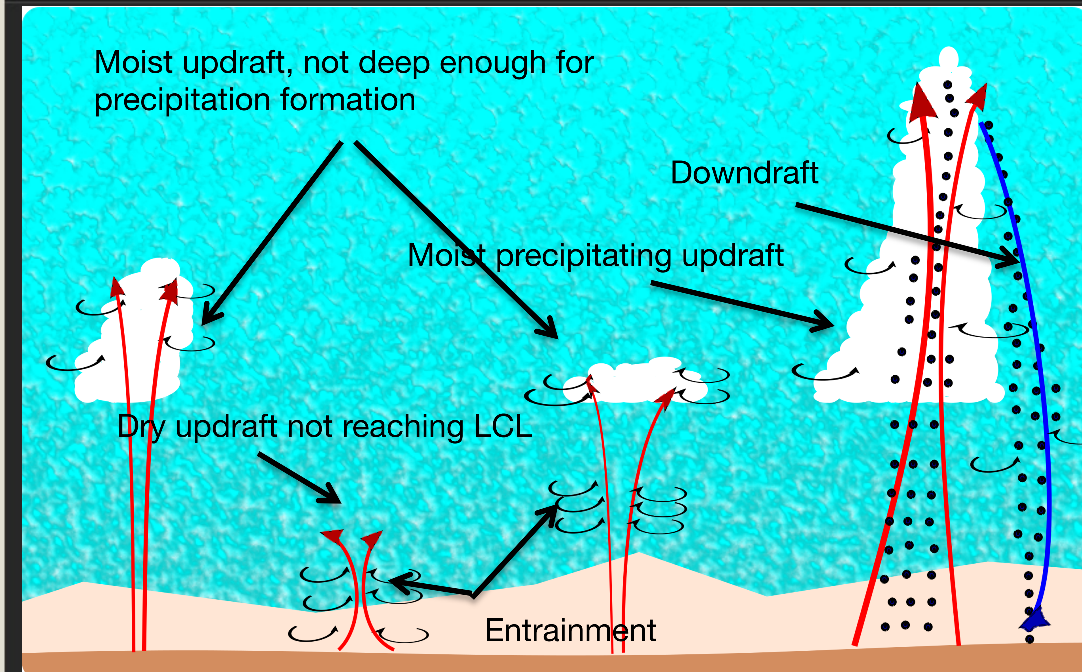
EDDY-DIFFUSIVITY/MASS-FLUX (EDMF) MODEL



EDMF framework - decomposition of a model grid-box into:

1. Multiple convective updrafts and/or downdrafts
2. Environment

i	Index representing thermals
E	Index representing environment
a_i, a_E	Fraction area of environment/ thermals
$\overline{\varphi}$	Mean values
φ'	Deviation from mean

First-order moments:

$$\overline{\varphi} = a_E \varphi_E + \sum_i a_i \varphi_i$$

Top-hat approximation for updrafts/downdrafts

Second-order moments:

$$\overline{\varphi'\psi'} = a_E \overline{\varphi'\psi'}|_E + a_E(\varphi_E - \overline{\varphi})(\psi_E - \overline{\psi}) + \cancel{\sum_i a_i \overline{\varphi'\psi'}_i} + \sum_i a_i(\varphi_i - \overline{\varphi})(\psi_i - \overline{\psi})$$

Eddy-diffusivity/mass-flux (EDMF) model

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KEY IDEAS

Mass-flux parameterization:

a) Updrafts

- Multiple steady-state surface-driven updrafts with constant fraction area
- At the surface – a tail of the (assumed joint normal) distribution $N(w, \theta_v, q_t)$
- Entrainment rate modeled as stochastic and discrete process
- Simple microphysics

b) Downdrafts

- Each precipitating updraft has a complementary downdraft
- Downdraft forced by evaporation of rain (negative buoyancy)
- Downdrafts modify surface distributions of thermodynamic variables and entrainment rate

Eddy-diffusivity parameterization:

- Eddy-diffusivity coefficient a function of ‘environmental’ *tke*
- Diagnostic length-scales in agreement with Quasi-Normal Scale Elimination (QNSE) theory

EDMF model – eddy-diffusivity

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EDDY-DIFFUSIVITY/VISCOSITY PARAMETERIZATION

$$\overline{\varphi' w'} = a_E \overline{\varphi' w'}|_E + a_E(\varphi_E - \overline{\varphi})(w_E - \overline{w}) + \sum_i a_i(\varphi_i - \overline{\varphi})(w_i - \overline{w})$$

$$\overline{\varphi' w'}_E = -K_{m;h} \frac{\partial \varphi}{\partial z}$$ ← Down-gradient approximation for environmental turbulent flux

$$K_{m;h} = l_{m;h}\sqrt{e_E}$$ ← Eddy-diffusivity coefficient a function of environmental *tke* (prognostic equation for mean *tke*)

$$l_{m,h} = l_0(kz, \tau\sqrt{e_E}, \sqrt{e_E}/N) \cdot \alpha_{m;h}(Ri)$$ ← Diffusive/viscosive length scale (diagnostic equation)

Stability function – QNSE theory

EDMF model – mass-flux

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UPDRAFT EQUATIONS

$$\overline{\varphi' w'} = a_E \overline{\varphi' w'}|_E + a_E(\varphi_E - \overline{\varphi})(w_E - \overline{w}) + \sum_i a_i(\varphi_i - \overline{\varphi})(w_i - \overline{w})$$

Multiple steady-state updrafts coupled with microphysics:

$$\frac{\partial \varphi_i}{\partial z} = \epsilon_i(\overline{\varphi} - \varphi_i) + \frac{S_i^{\varphi}}{w_i} \qquad \varphi = \{u, v, \theta_L, q_t\}$$

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

$$RRi(z) = \int_z^{\infty} \rho S_i^{q_t}(1-f)dz$$

ϵ_i	Entrainment coefficient
B_i	Updraft buoyancy
S_i^{φ}	Rate of microphysical processes
w_i	Updraft vertical velocity
a, b	Constants for vertical velocity eq.
RR	Rain rate
f	Fraction of rain falling out of updr

EDMF model – mass-flux

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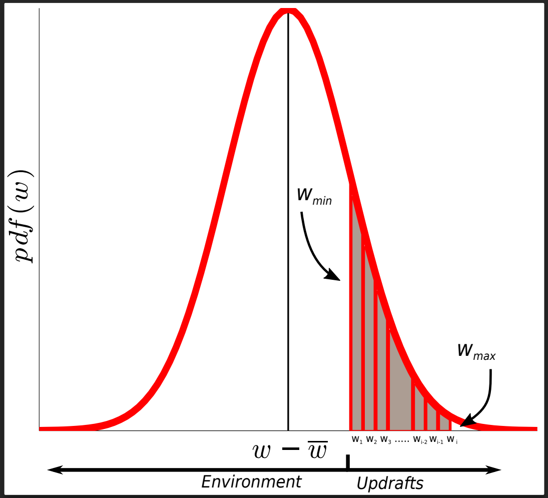
WHY DO THE UPDRAFTS DIFFER?

1. Surface conditions differ for each updraft
   - Updrafts represent surface driven plumes
   - Discretized tail of assumed joint normal distribution of surface w, θ_v and q_t (Cheniet 2003)
   - Number of updrafts and the total updraft area – model choice (see sensitivity study)
2. Entrainment rate parameterization
   - Stochastic discrete process
   - Probability of entrainment the same for all plumes, actual entrainment is one realization



EDMF results – marine shallow convection

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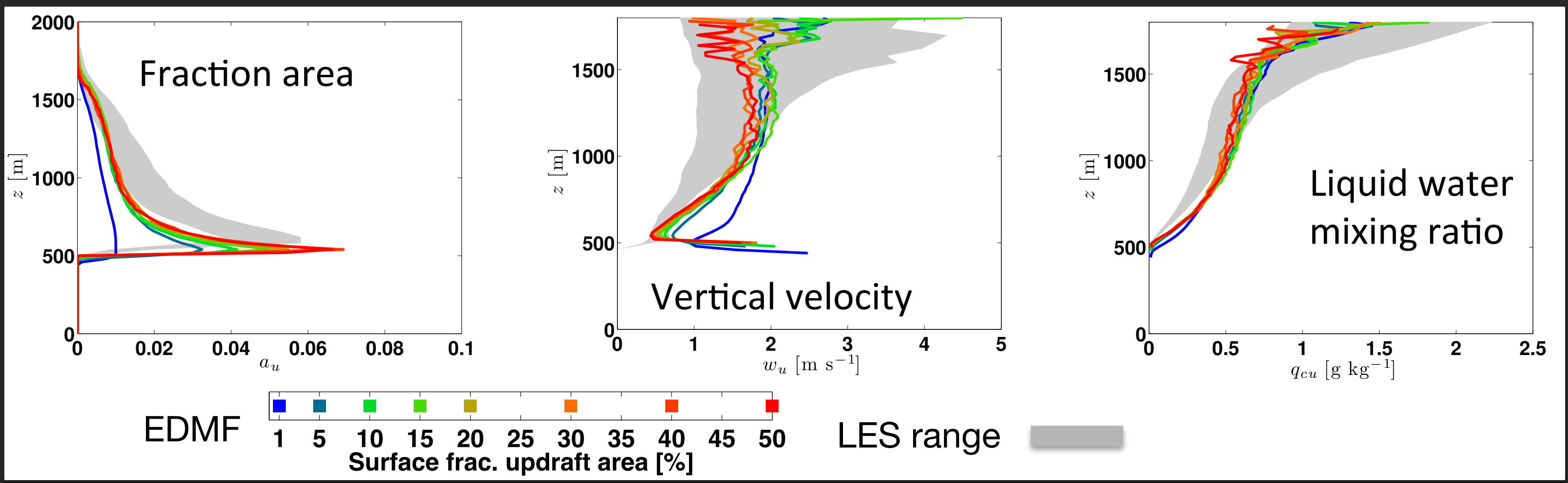
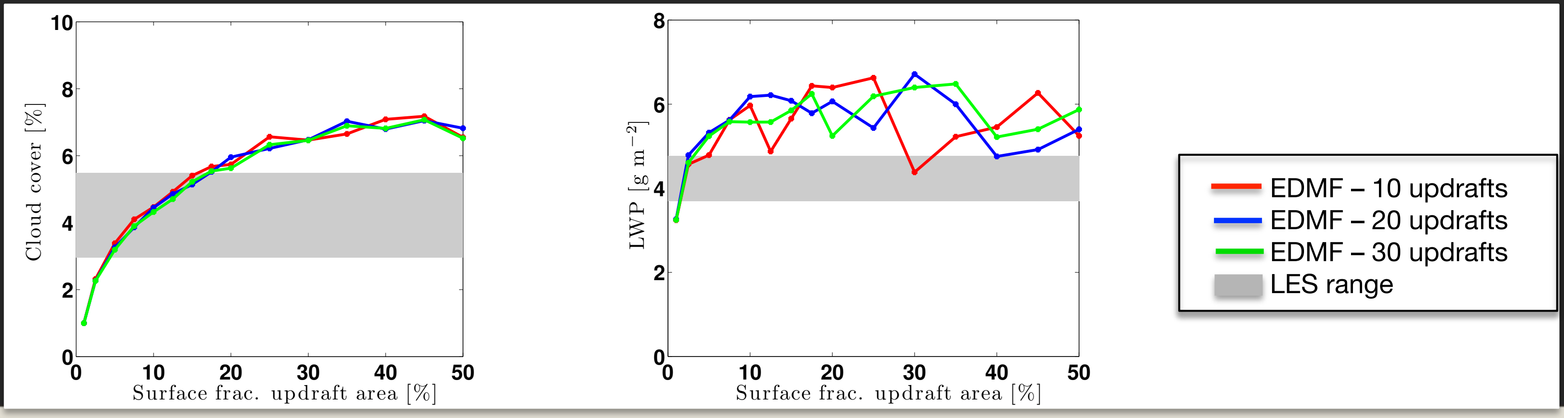
BOMEX CASE (SIEBESMA ET AL., 2003): MASS-FLUX REPRESENTATION OF CUMULUS CONVECTION

Comparison of EDMF moist updrafts/cloud properties against LES results



Low sensitivity of the EDMF results to selection of surface updraft area & number of updrafts



EDMF results – marine precipitating convection

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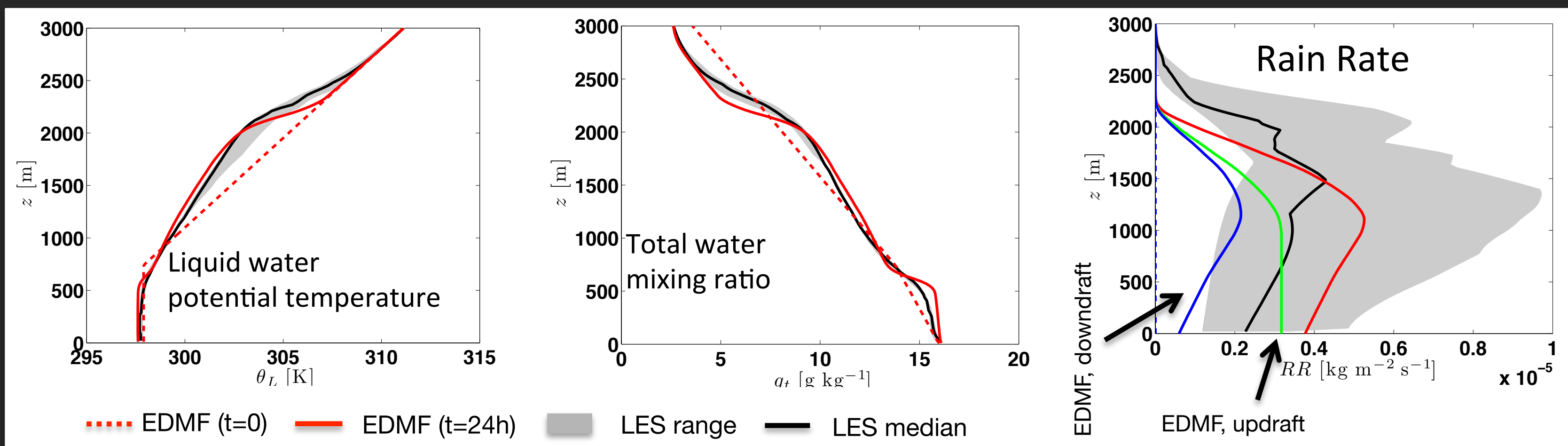
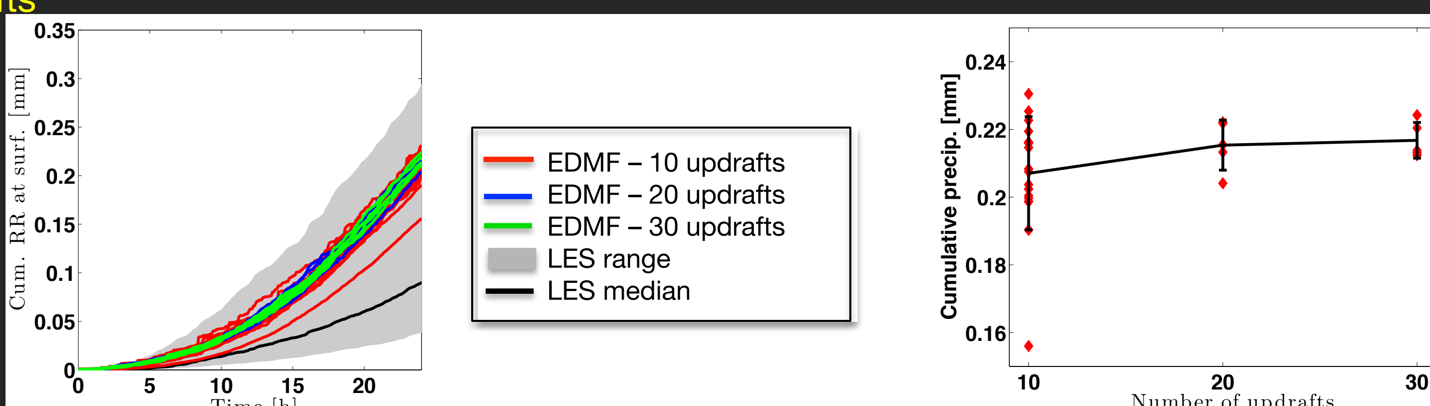
RICO CASE (VAN ZANTEN ET AL., 2014)

Comparison of EDMF moist updrafts against LES results – profiles after 24 hours of simulation

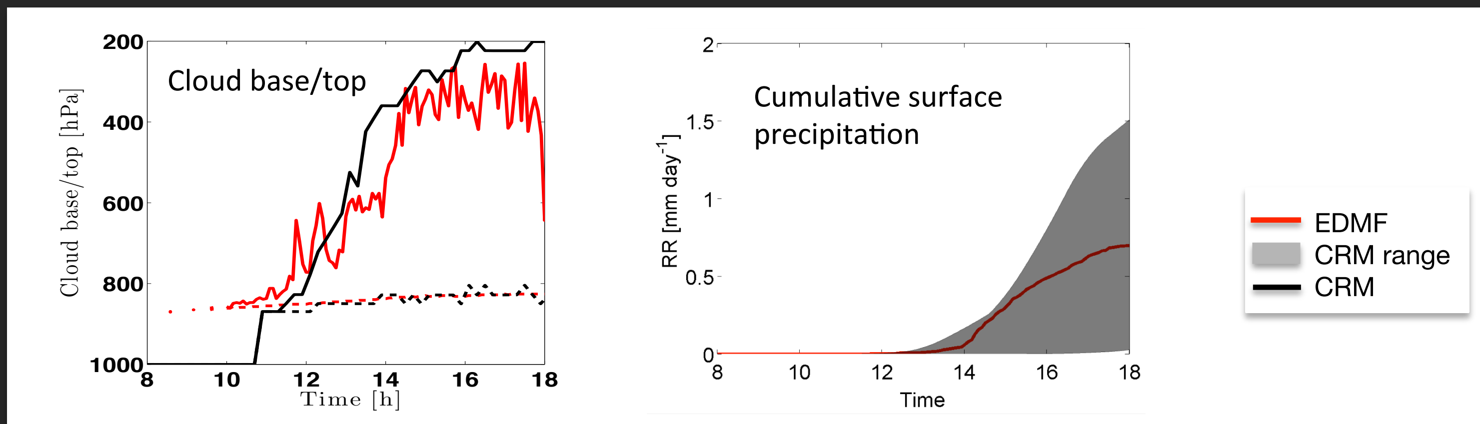


Cumulative surface precipitation: difference between EDMF realizations & sensitivity to the number of updrafts



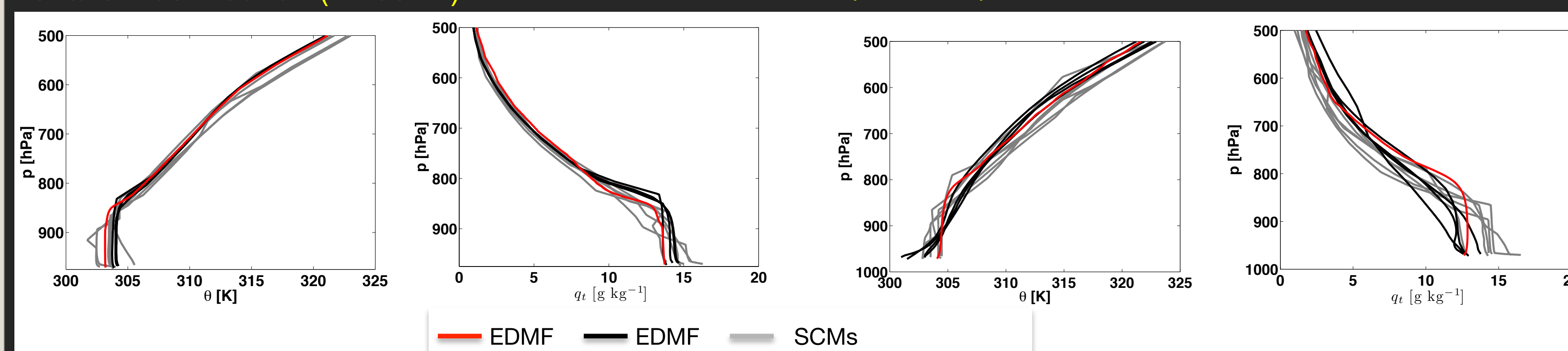
EDMF results – diurnal cycle of precipitating convection over land

EUROCS CASE (GUICHARD ET AL., 2004)



Profiles of thermodynamic variable at the onset of shallow convection (12:00 LT)

Profiles of thermodynamic variable in the afternoon (18:00 LT)



Final thoughts

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MULTI-PLUME STOCHASTIC MODEL

- Realistically simulate different surface driven convection regimes:
  a. Dry convection
  b. Moist non-precipitating
  c. Shallow precipitating
  d. Deep convection
- No CAPE/CIN-type closure needed
- Low sensitivity to most of the model choices (e.g. number of updrafts, surface updraft fraction area)
- Coupling of microphysics and turbulence dynamics is done in a physically consistent way
- Easily implemented in a fully 3D weather prediction/climate model:
  a. Proven to be successful in weather prediction model (operational NAVGEM model; Šušelj et al., 2014)
  b. Implementation in WRF model – see Poster "Cloud response to Eddy Diffusivity Mass Flux (EDMF) based Boundary Layer Parameterization" by R. Bhattacharya et al.

Thank you for your attention