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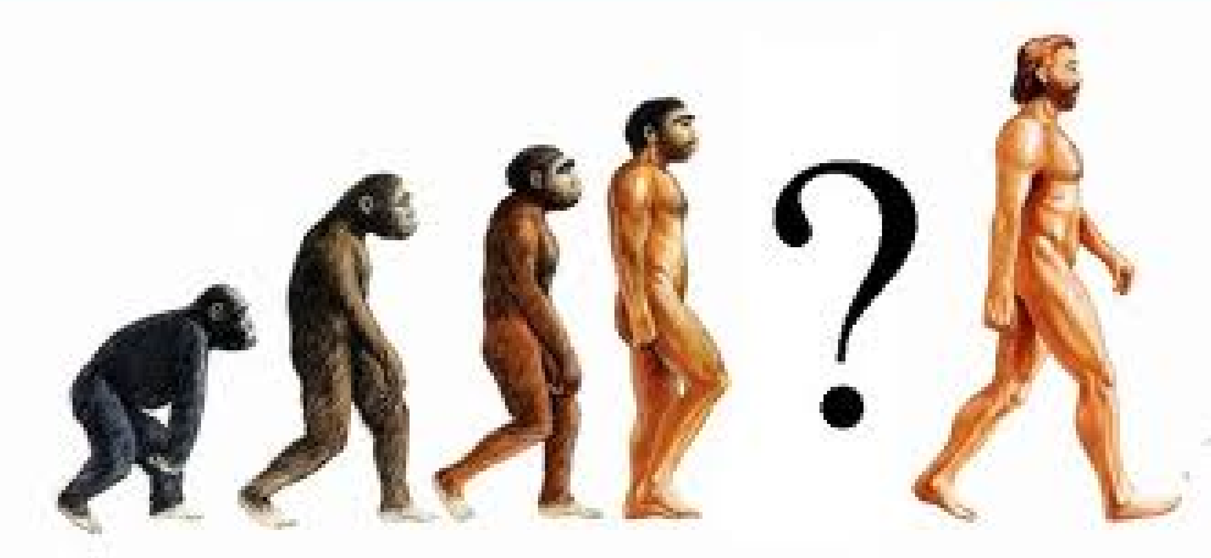
I. An integrated TKE based eddy-diffusivity/mass-flux scheme for the dry CBL

II. An EDMF approach to the vertical transport of TKE



Model domain:

8 x 8 x 4(5) km

resolution 20m

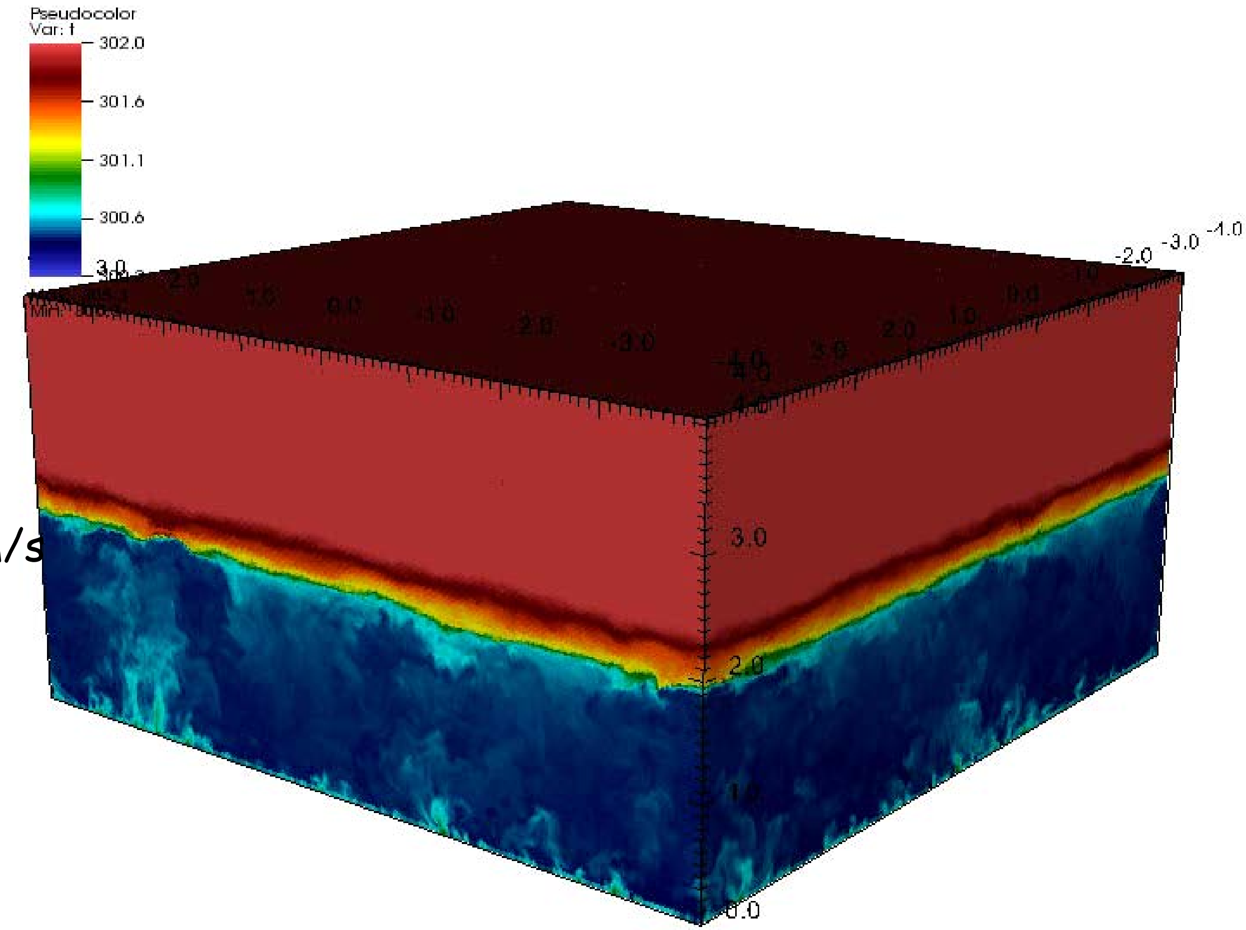
Surface fluxes

heat:

(0.03,0.06,0.09,0.12) Km/s

humidity:

2.5×10^{-5} m/s



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PART 1

Combined TKE-EDMF scheme

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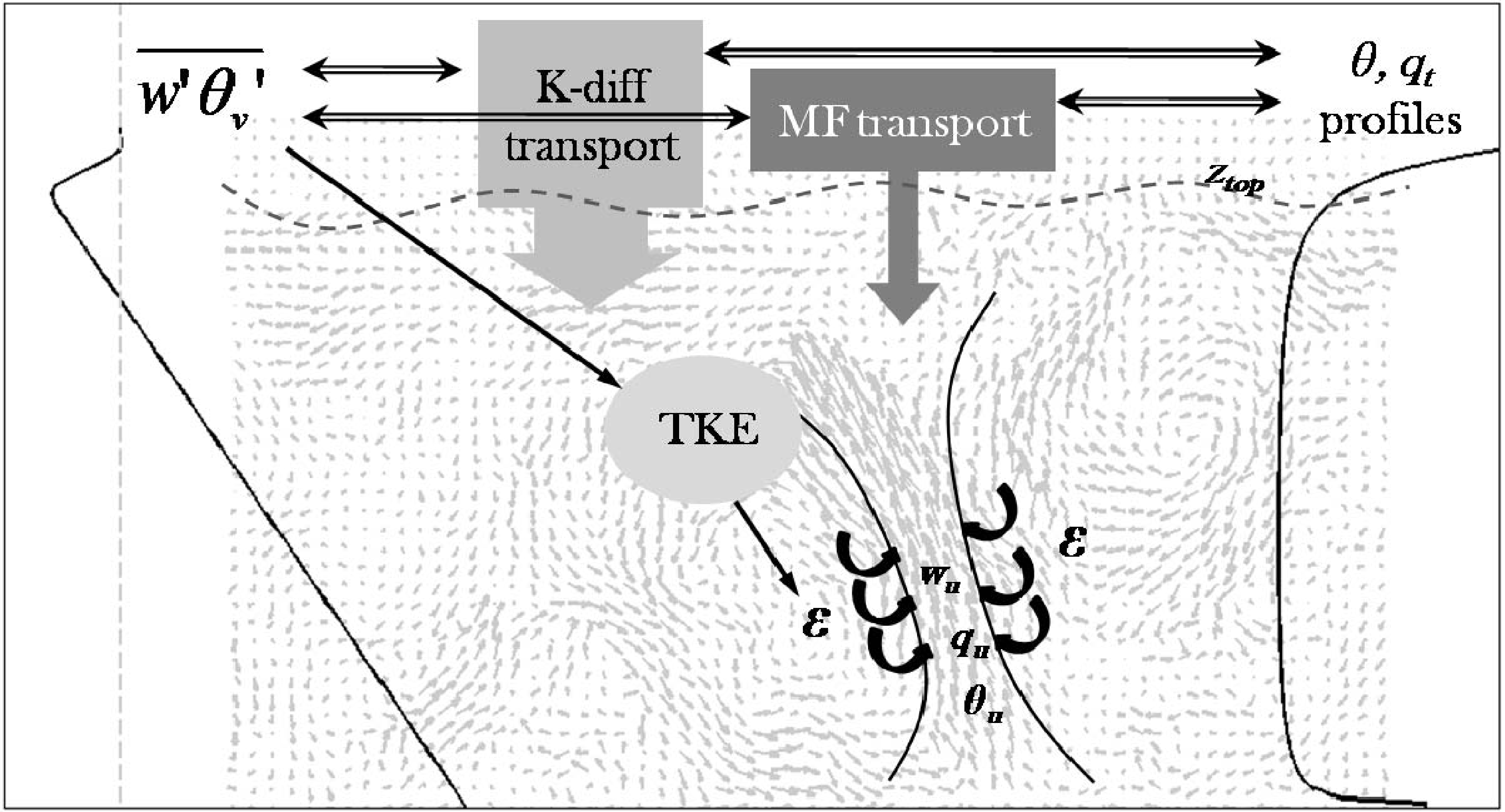
$$\overline{w'\varphi'} \cong \overline{w'\varphi'}^{e} + M\left(\varphi_u - \overline{\varphi}\right)$$



TKE impacts both ED and MF transport terms

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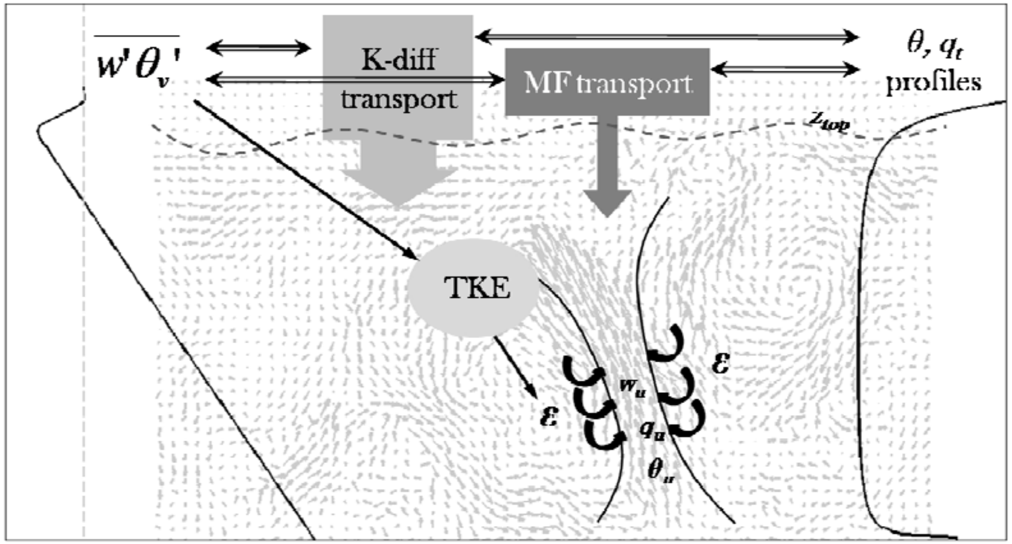
Scalar prognostic equation:

$$\frac{\partial \bar{\phi}}{\partial t} = -\frac{\partial \overline{w'\phi'}}{\partial z} + F_{\phi}$$



EDMF concept :
(Siebesma and Teixeira, 2000)

$$\overline{w'\phi'} \cong -K_{\phi}\frac{\partial \bar{\phi}}{\partial z} + M\left(\phi_u - \bar{\phi}\right)$$

Mass-flux term:

$M = \rho\sigma w_u$ Unknown: $\sigma, w_u, \phi_u, \varepsilon$

Assumption: $\sigma = 0.1$ - we simulate the strongest 10% of the *w* distribution

$$w_u\frac{\partial w_u}{\partial z} = -\varepsilon b_1 w_u^2 + b_2 F_{w,u} \qquad \varepsilon = a\frac{1}{l}$$

$$\frac{\partial \phi_u}{\partial z} = -\varepsilon\left(\phi_u - \bar{\phi}\right)$$

Entrainment coefficient: exchange of properties between updrafts and environment

Eddy-diffusivity term:

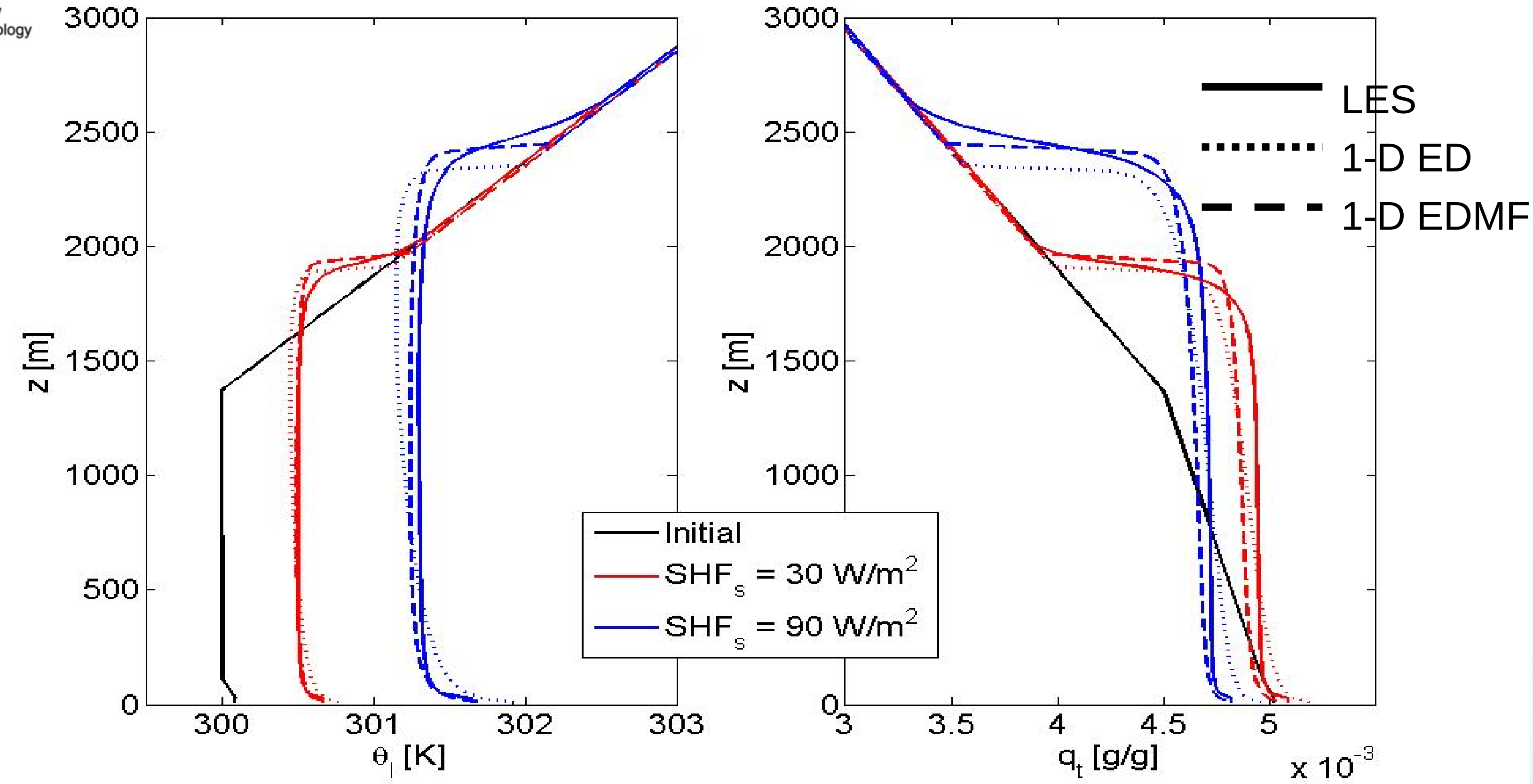
$$K_{\phi,e} = C_k l\sqrt{e} \qquad l^{-1} = l_1^{-1} + l_2^{-1}$$

$l_1 = \tau\sqrt{e}$ – Teixeira and Cheinet (2004)

$l_2 = kz f\left(z/L\right)$ – e.g. Nakanishi (2001)

$$\tau = 0.5\frac{z_{top}}{w_*}$$

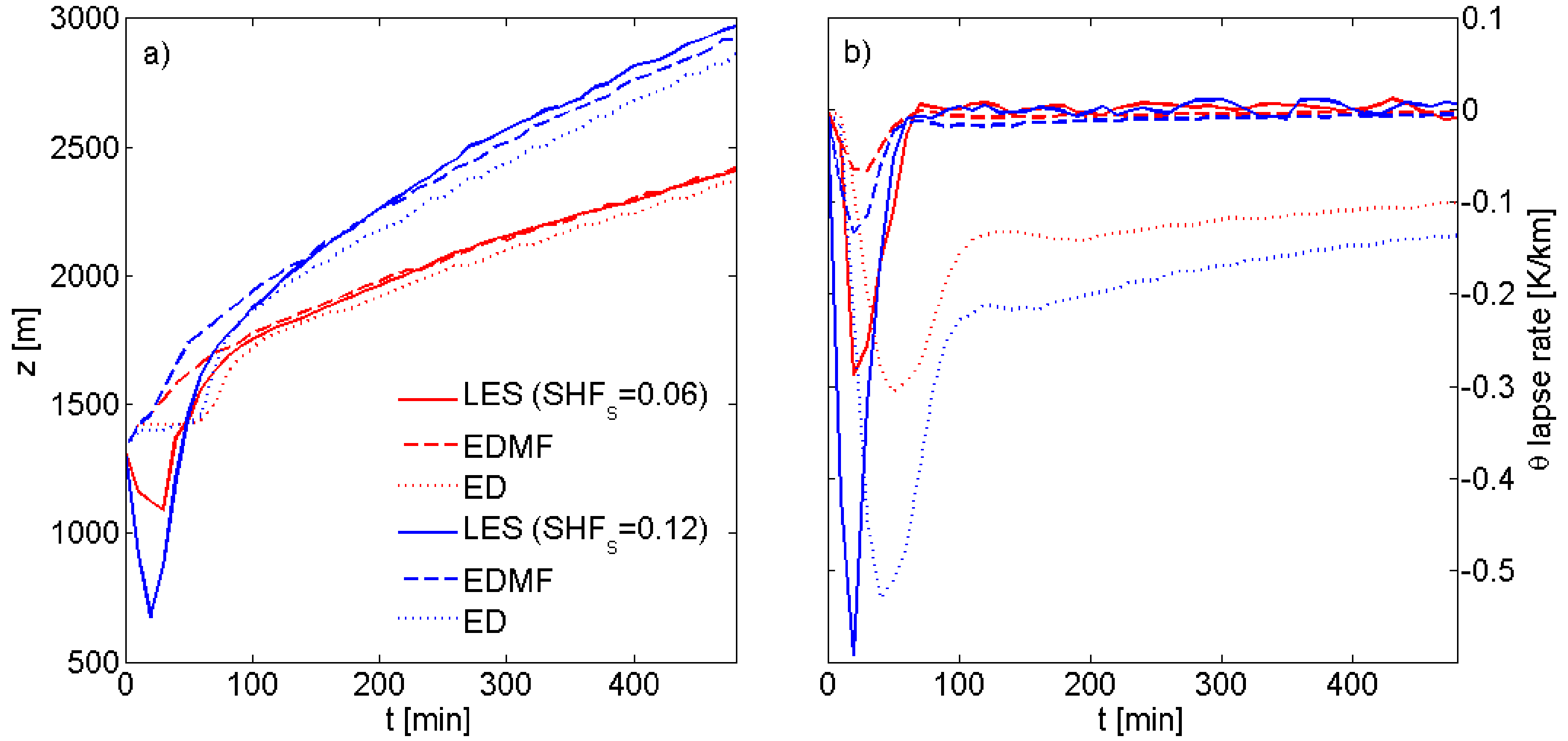
θ and q_t vertical profiles after 6 hours



Pros
- surface layer more realistic
- neutral profile in the well-mixed layer
- larger entrainment leads to better inversion height

Cons
- inversion layer too sharp compared to LES
- q_t not sufficiently well mixed

Boundary layer height (a) and θ lapse rate (b) evolutions



Good behavior in time, after initial spin-up effects

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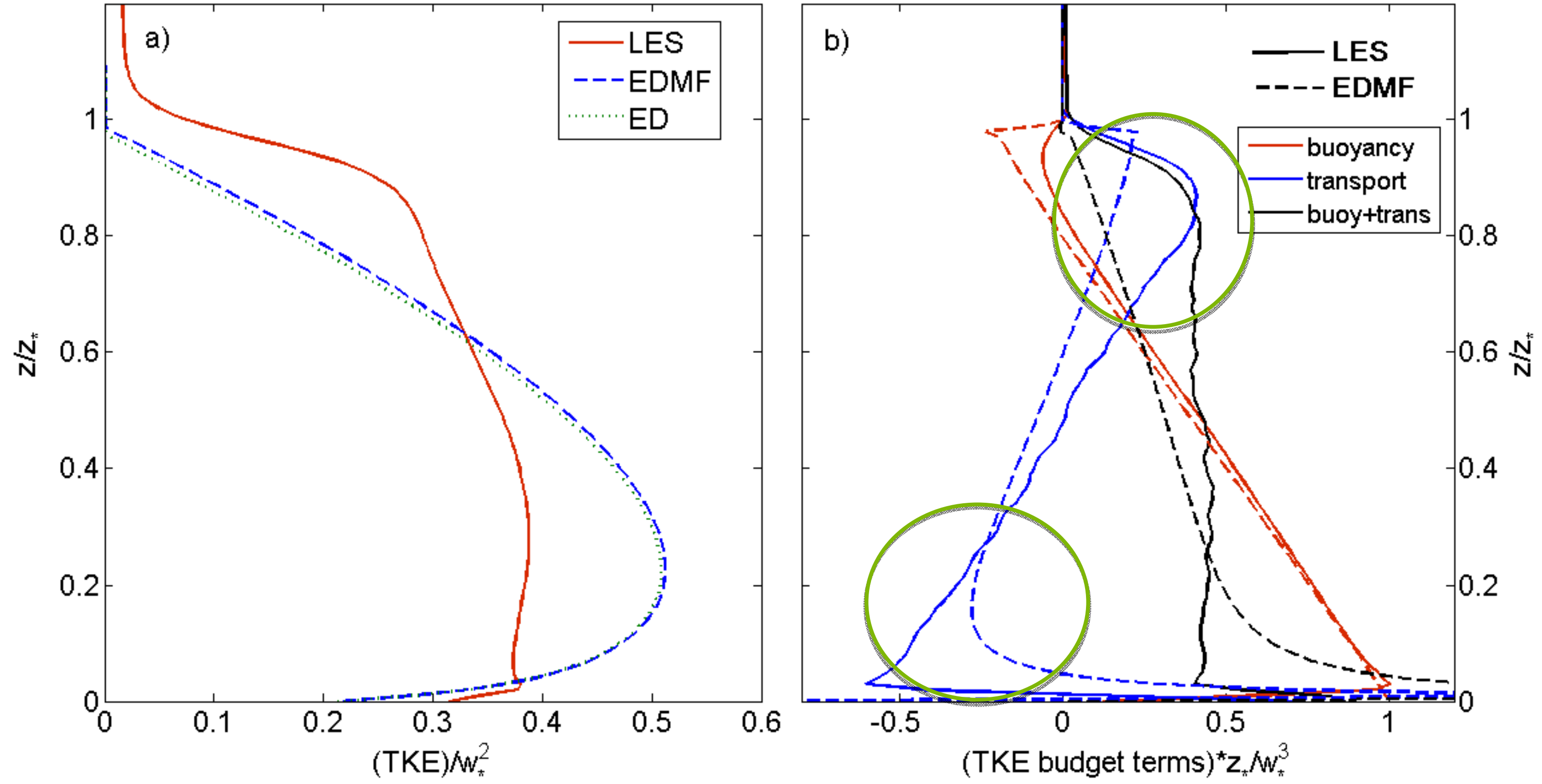
Normalized TKE profile and TKE budget

$$trans = -\frac{\partial \overline{w'e'}}{\partial z} - \frac{\partial \overline{w'p'}}{\partial z}$$



- 1D model does not resolve TKE profile sufficiently well, underestimating TKE close to the inversion
- Improvements are needed: mass-flux transport of TKE (or some other transport terms… wait for part 2)

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Lateral entrainment parameterizations comparison

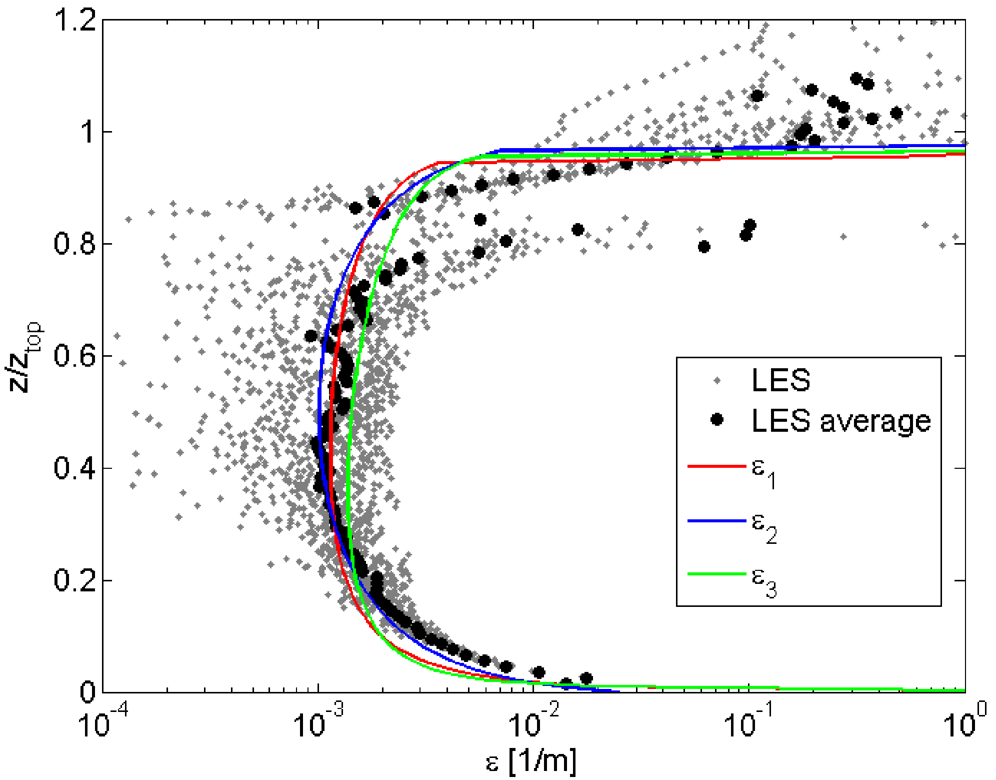
ε diagnosed from LES

$$\frac{\partial \phi_u}{\partial z} = -\varepsilon\left(\phi_u - \bar{\phi}\right)$$

$$\varepsilon_1 = a_1 \frac{1}{l}$$

$$\varepsilon_2 = a_2\left(\frac{1}{z+\Delta z} + \frac{1}{\left(z_{top} - z\right) + \Delta z}\right)$$

$$\varepsilon_3 = a_3 \frac{1}{\tau w_u}$$



- Good agreement between LES-diagnosed and parameterized ε values
- Small differences between various parameterizations

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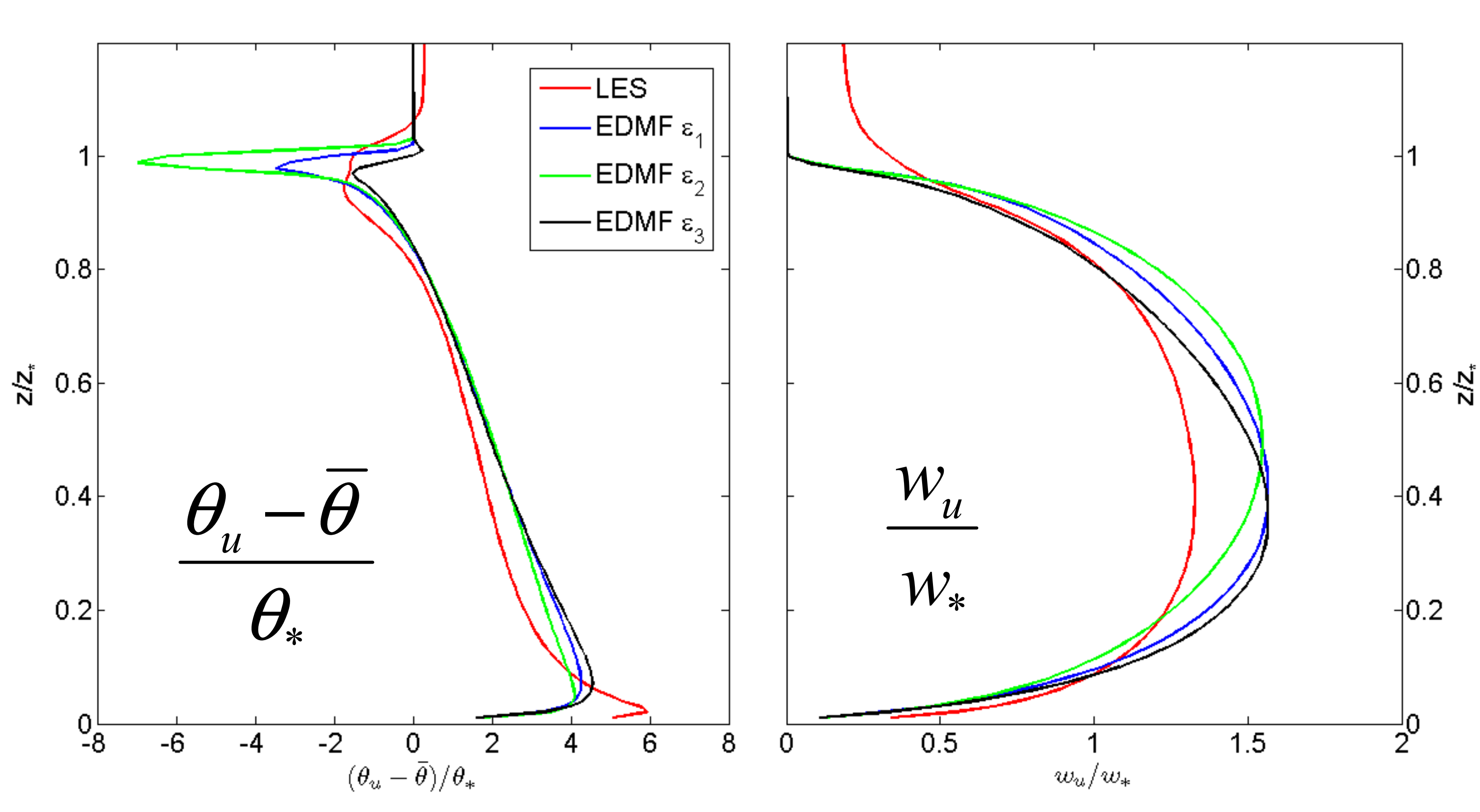
Updraft characteristics



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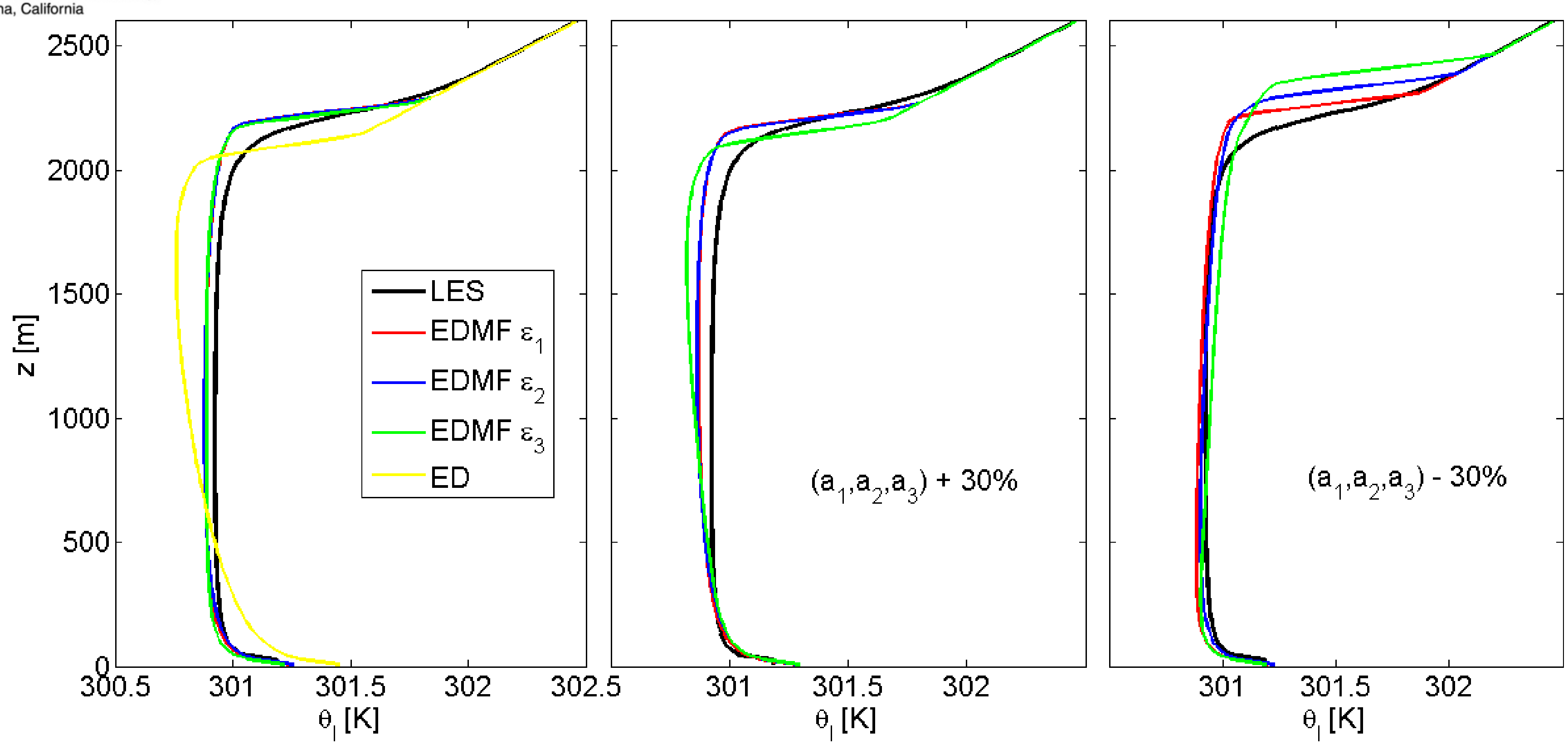
Some additional sensitivity studies:



- All ε parameterizations can simulate CBL very well
- Changing parameters a_1, a_2 and a_3 indicates the robustness of each approach
- ε based on TKE has some advantages over the other parameterizations

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Can we extend TKE based ε parameterization to the shallow convection ?

… preliminary results

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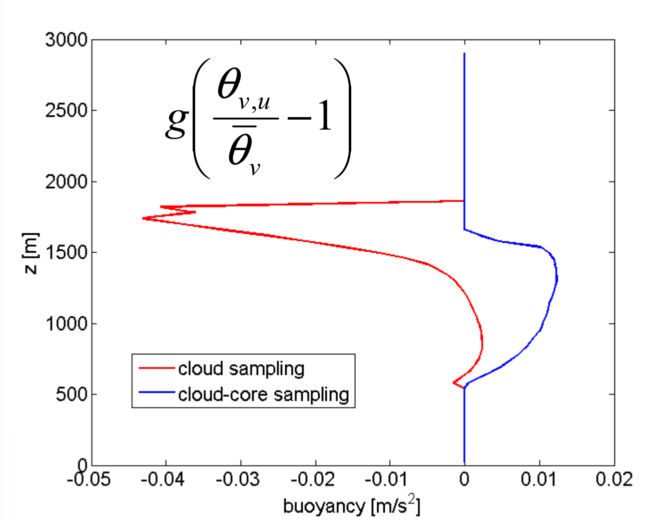
Entrainment parameterization in moist convection: BOMEX case

Three ways of diagnosing ε based on LES results:

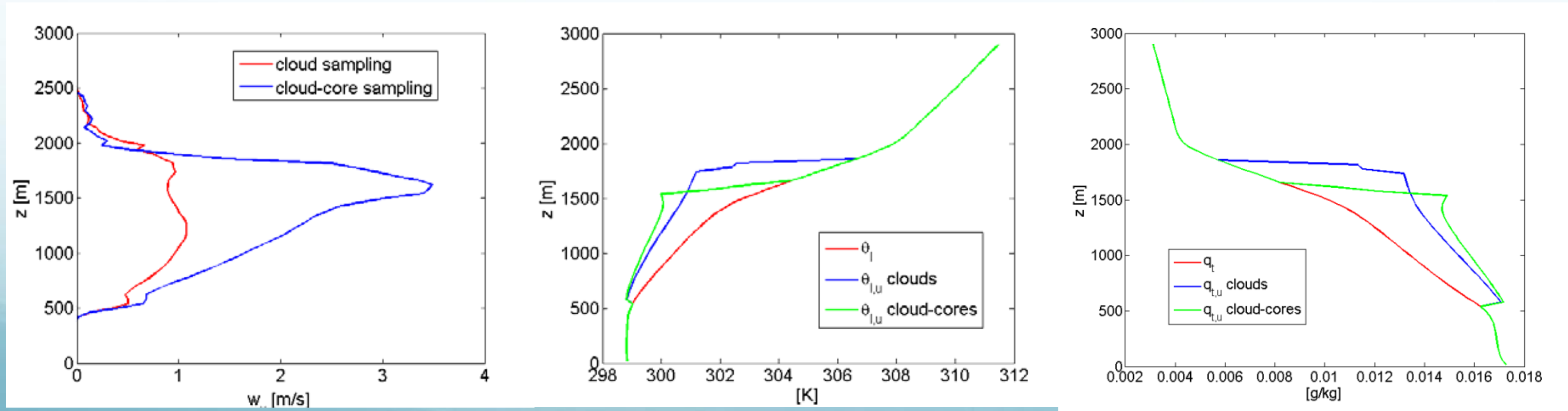
$$\frac{\partial \theta_{l,u}}{\partial z} = -\varepsilon\left(\theta_{l,u} - \bar{\theta}\right)$$

$$\frac{\partial q_{t,u}}{\partial z} = -\varepsilon\left(q_{t,u} - \bar{q}_t\right)$$

$$w_u \frac{\partial w_u}{\partial z} = -\varepsilon b_1 w_u^2 + b_2 g\left(\frac{\theta_{v,u}}{\bar{\theta}_v} - 1\right)$$



Additional sampling distinction: clouds & cloud-cores



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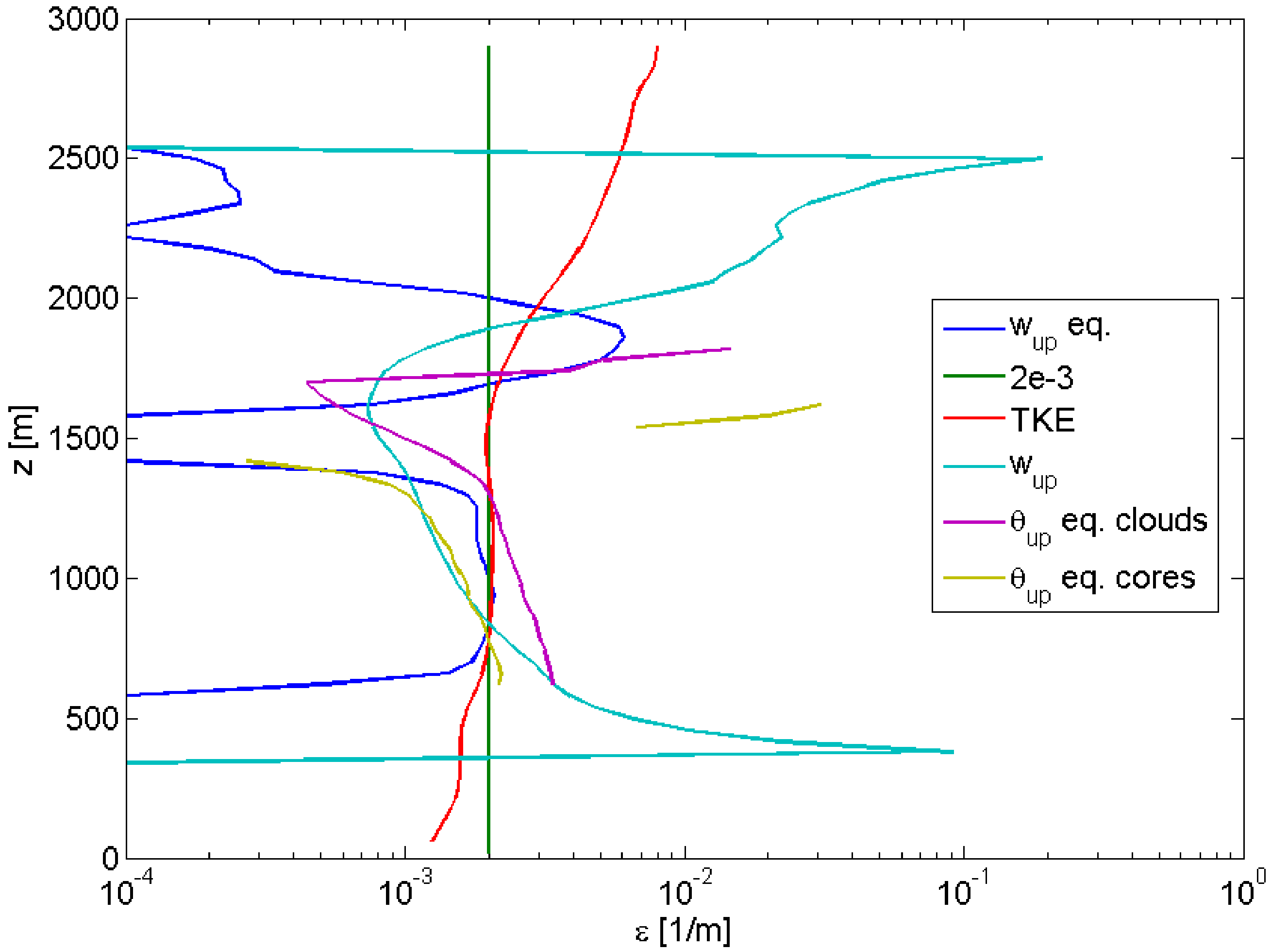
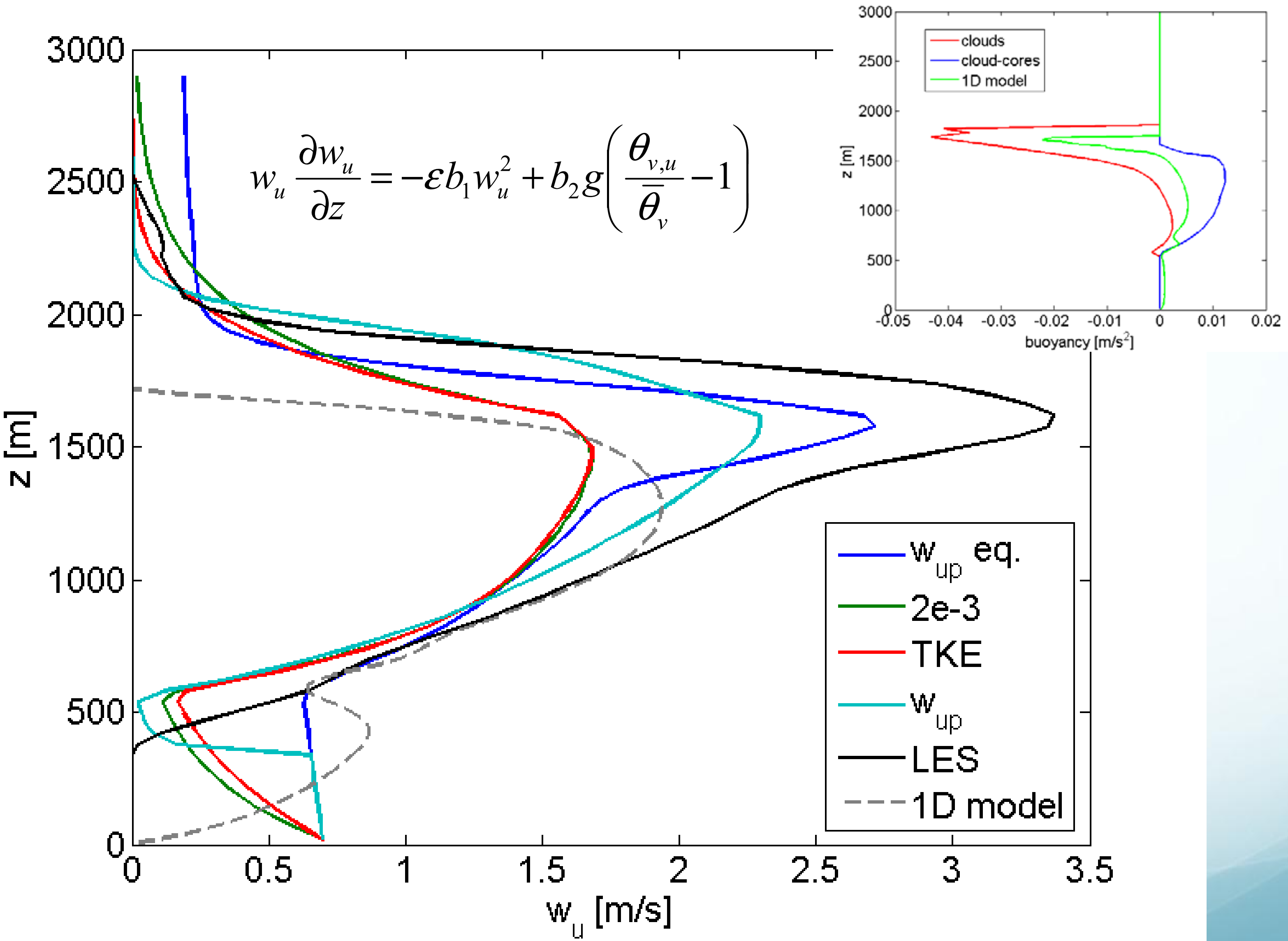
Entrainment diagnostics and parameterizations: BOMEX case



$$w_{up} \mapsto \varepsilon = \frac{1}{400 w_u} \qquad TKE \mapsto \varepsilon = \frac{1}{1500\sqrt{e}} \qquad 1500 \approx \tau = 0.5\frac{z_{top}}{w_*}$$

How these parameterizations actually perform?



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PART 2

EDMF for vertical transport of TKE

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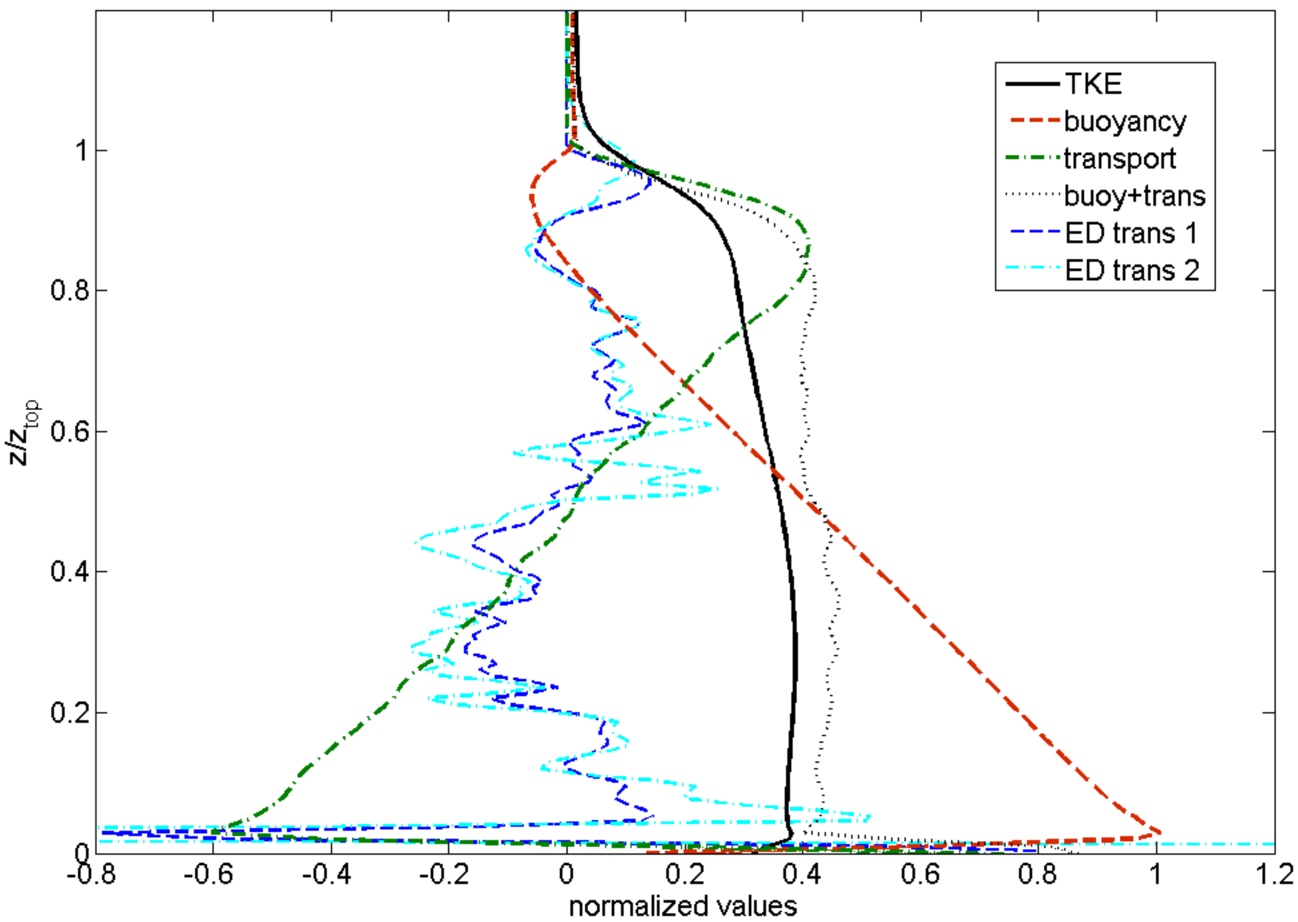
Motivation

$$\frac{\partial \overline{w'e}}{\partial z} + \frac{1}{\rho}\frac{\partial \overline{w'p'}}{\partial z} \cong \frac{\partial}{\partial z}\left(-K\frac{\partial e}{\partial z}\right)$$



"ED trans 1" and "ED trans 2": TKE transport based on ED parameterization

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Equations and parameterizations:

$$\frac{\partial e}{\partial t} = \frac{g}{\overline{\theta}_v}\overline{w'\theta_v'} - \frac{\partial \overline{w'e}}{\partial z} - \frac{1}{\rho}\frac{\partial \overline{w'p'}}{\partial z} - \varepsilon - \overline{u'w'}\frac{\partial \overline{u}}{\partial z} - \overline{v'w'}\frac{\partial \overline{v}}{\partial z}$$

$$\frac{\partial \overline{w'e}}{\partial z} = \frac{1}{2}\left(\frac{\partial \overline{w'u'^2}}{\partial z} + \frac{\partial \overline{w'v'^2}}{\partial z} + \frac{\partial \overline{w'w'^2}}{\partial z}\right)$$

Updraft-environment decomposition

$$\overline{w'^3} \cong \overline{w'^3}^e + \sigma(1-\sigma)(1-2\sigma)(w_u - w_e)^3$$

$$\overline{w'e} \cong \overline{w'e}^e + \frac{1}{2}\sigma\frac{1-2\sigma}{(1-\sigma)^2}w_u^3$$

$$\frac{\partial \overline{w'e}}{\partial z} + \frac{1}{\rho}\frac{\partial \overline{w'p'}}{\partial z} \cong \frac{\partial}{\partial z}\left(-K\frac{\partial e}{\partial z}\right) + \frac{3}{2}\sigma w_u^2\frac{\partial w_u}{\partial z}\left(1 - \frac{\sigma^2}{(1-\sigma)^2}\right)$$

TKE transport $\cong$ *ED term* + *MF term*

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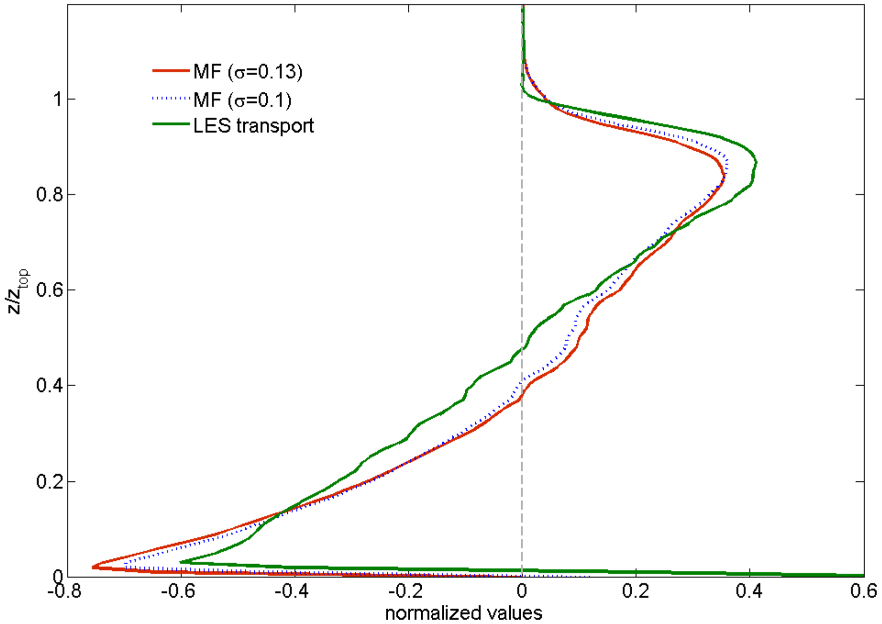
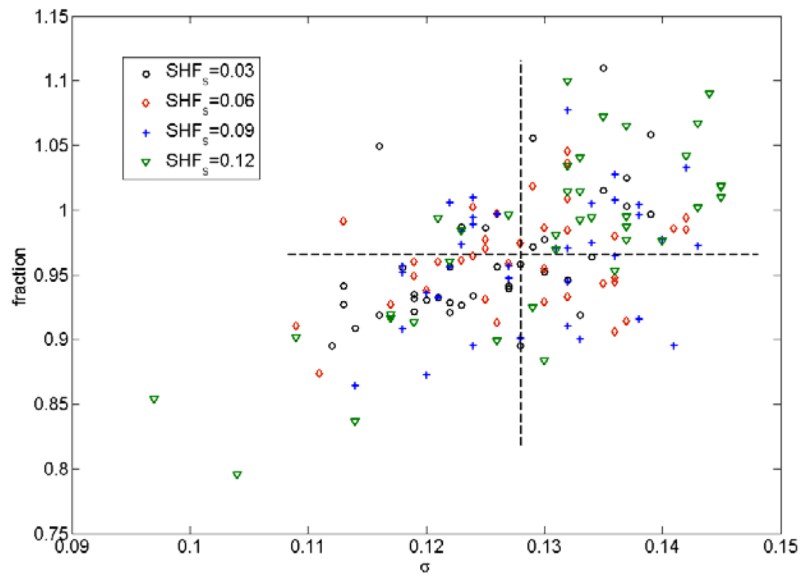
Verification with LES



What is an optimal updraft fraction?



Simplified 1D TKE simulations (most terms prescribed based on LES)

$$\frac{\partial e}{\partial t} = \frac{g}{\theta_v}\overline{w'\theta_v'} - \varepsilon - \frac{\partial}{\partial z}\left(-K\frac{\partial e}{\partial z}\right) - \alpha\sigma w_u^2 \frac{\partial w_u}{\partial z}$$

Minimum difference between the MF term and the LES transport

- updraft fraction 0.13
- 97% of LES trans. resolved

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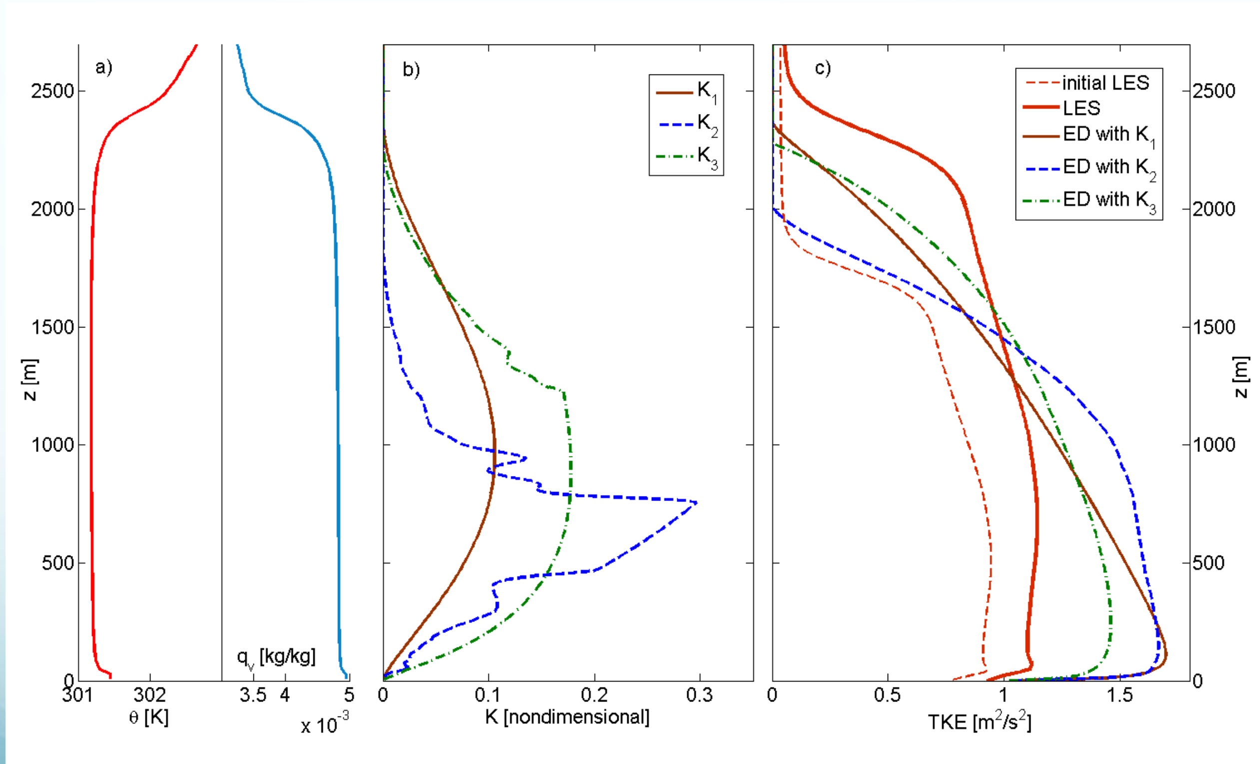
	K_1	K_2	K_3
Expression and references	$K_1 = K_1\left(\frac{z}{z_{top}}, u_*, w_*\right)$ Holtslag (1998)	$K_2 = l_2 S_h \sqrt{e}$ Bretherton and Park (2009)	$K_3 = a_3 l_3 \sqrt{e}$ Witek et al. (2011), Galperin et al. (1988)
Surface layer scaling	Prescribed	kz	$kz\, f(L)$
Static stability scaling	Prescribed	Embedded in S_h $S_h = S_h(N^2, l_2, e)$	Embedded in l_3 $l_3 = \min[l_3, g(N,e)]$



- Underestimated TKE in lower parts of CBL
- ED is not sufficiently transporting TKE upwards
- ED fails to resolve relatively constant TKE within CBL

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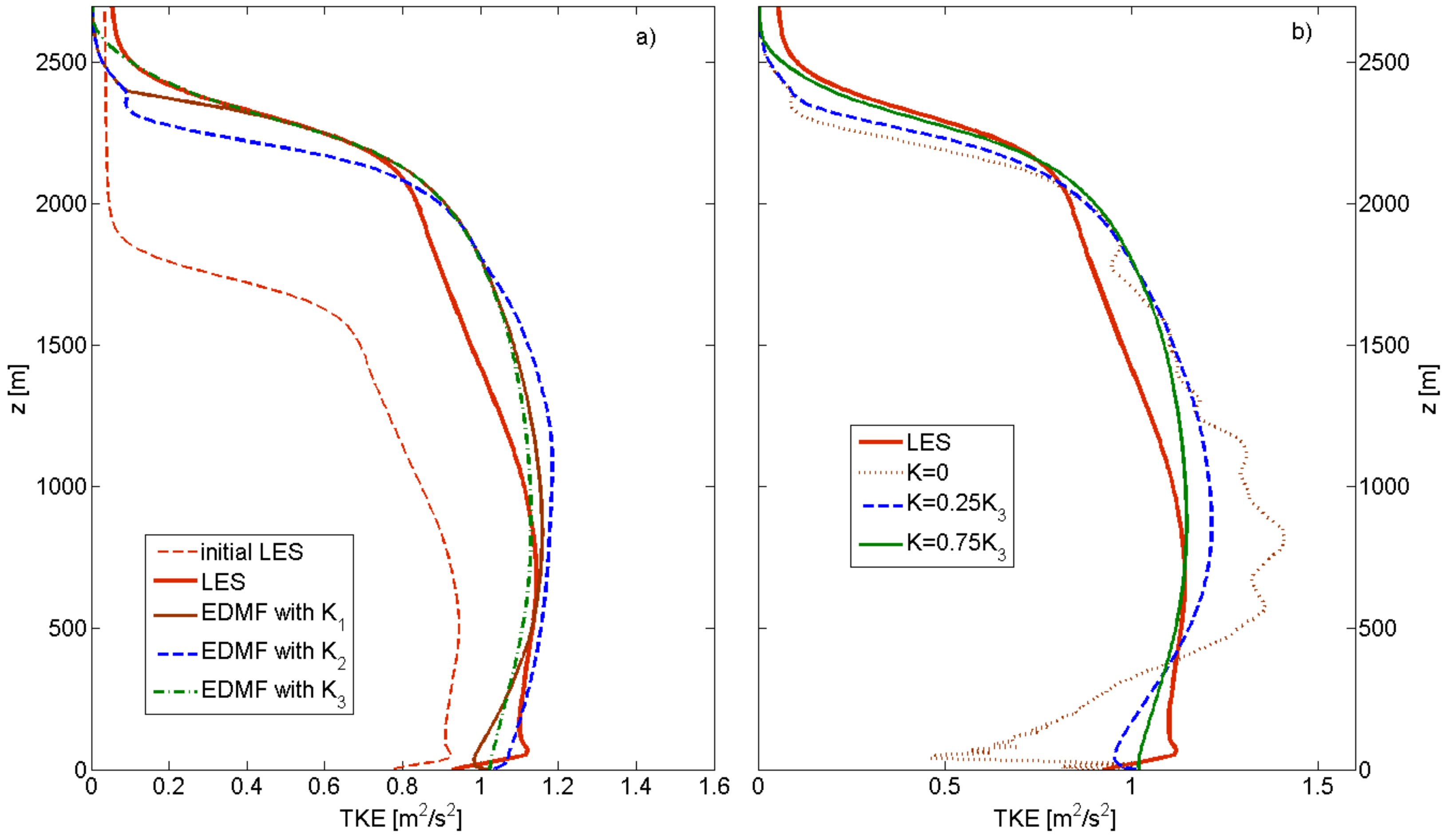
Evaluation



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Conclusions

1. Dry CBL can be simulated very well using the proposed integrated TKE-EDMF scheme.

2. TKE based ε parameterization can be potentially extended to shallow convection.

3. The new MF TKE transport term improves simulations of TKE