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Eddy-diffusivity/Mass-flux PBL parameterization: Dry convection and stratocumulus cases

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Motivation

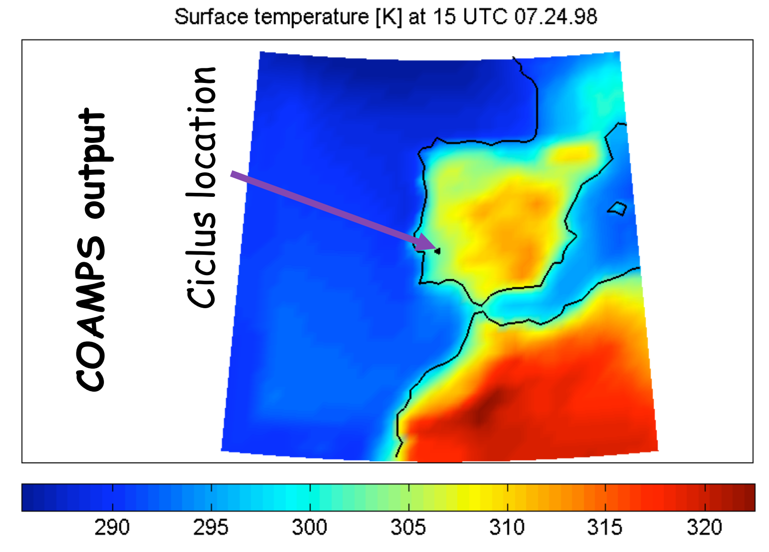
To improve PBL parameterizations in weather forecast and climate models

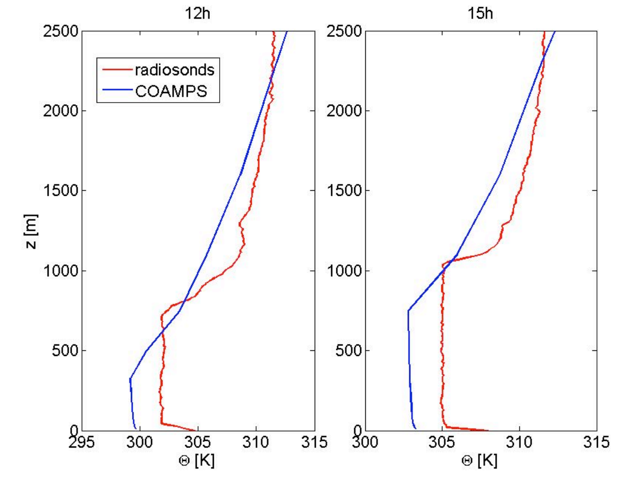
- Dry convective boundary layer
- Shallow cumulus
- Stratocumulus
- Deep convection

Numerical models still have problems simulating dry boundary layers

Realistic simulation of dry convection is an essential stepping stone for tackling cloudy boundary layers

Coupled Ocean-Atmosphere Mesoscale Prediction System (COAMPS) simulations

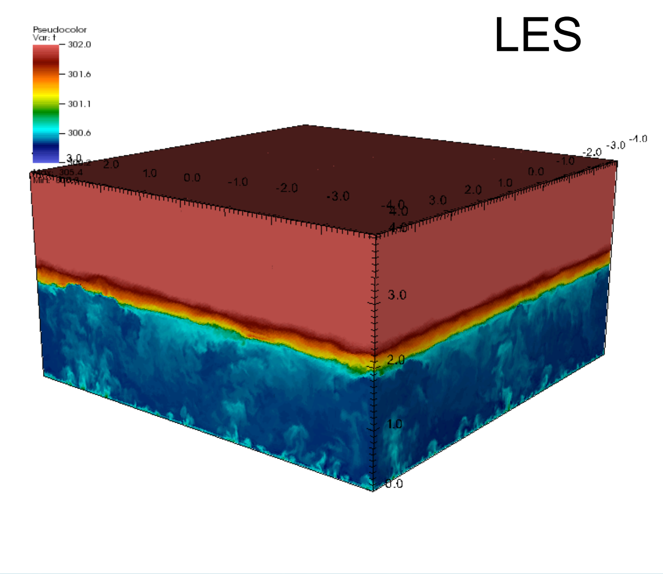


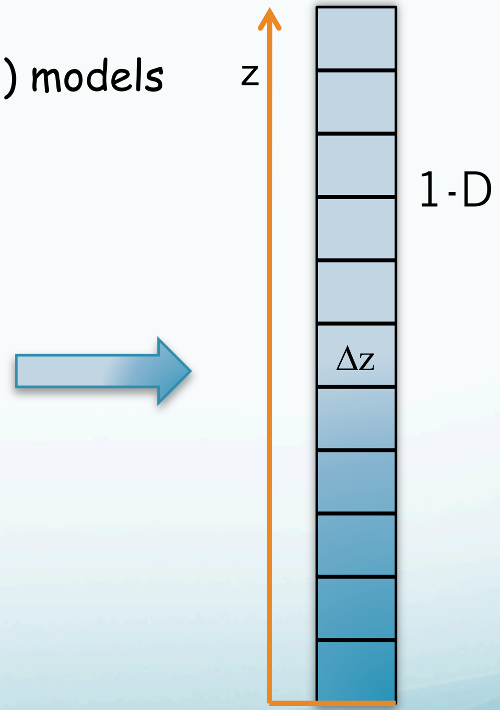


Strategy

- more coherent and effective parameterizations
- Eddy-diffusivity/Mass-flux (EDMF) approach
- TKE prognostic equation
- Surface stability scaling
- PDF based cloud scheme

Tools: 1-D and Large Eddy Simulation (LES) models





Dry convective PBL: free convection limit

Scalar prognostic equation: $$\frac{\partial \overline{\phi}}{\partial t} = -\frac{\partial \overline{w'\phi'}}{\partial z} + F_{\phi}$$

EDMF concept :
(Siebesma and Teixeira, 2000)

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

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

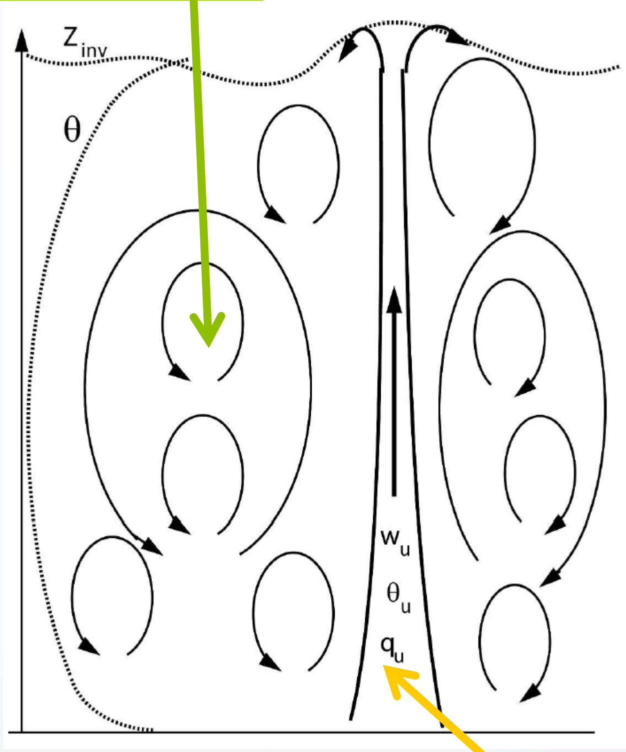
$$w_u \frac{\partial w_u}{\partial z} = -\varepsilon b_1 w_u^2 + b_2 F_{w,u}$$

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

$$\varepsilon = \alpha \frac{1}{l}$$

Entrainment coefficient – exchange of properties between updrafts and environment

eddy-diffusivity mixing
(small eddies)



mass-flux transport
(strong buoyant updrafts)

Fig. source: Siebesma et al. (2007)

Eddy-diffusivity term:

$$K_{\phi,e} = C_k l \sqrt{e}$$

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

$$l^{-1} = l_1^{-1} + l_2^{-1}$$

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

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

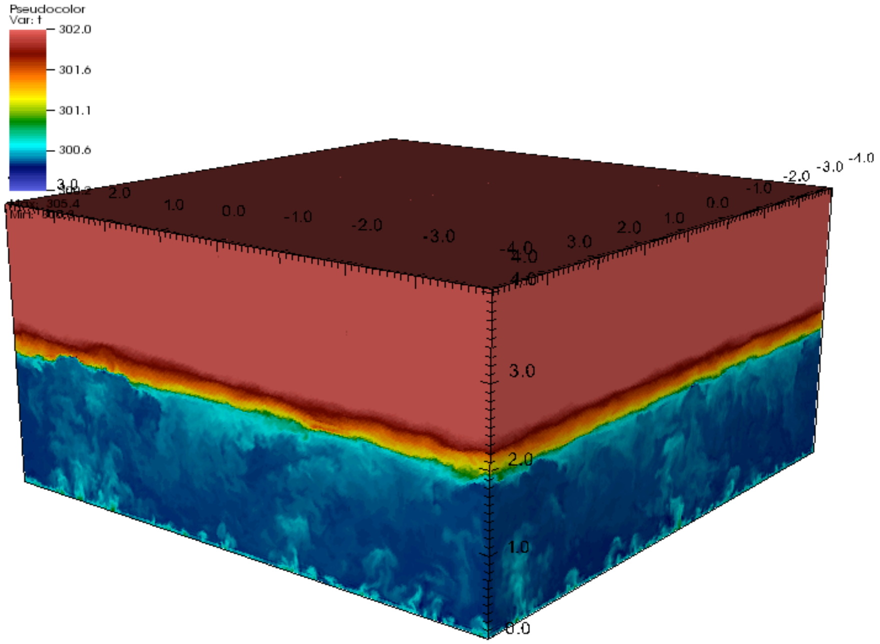
$$\tau = a \frac{z_{inv}}{w_*}$$

$$\frac{\partial e}{\partial t} = -\frac{\partial}{\partial z}\left(-K_e \frac{\partial e}{\partial z}\right) + \frac{g}{\overline{\theta}}\overline{w'\theta_v'} - D$$

$$D = C_e e^{3/2}/l$$

- Important parameters: l and τ
- Closure based on e, surface stability, surface sensible heat flux and inversion height
- Minimal number of ad-hoc parameters

LES experiments: dry convective boundary layer with various surface heat fluxes



LES setup:

$\Delta x = \Delta y = \Delta z = 20$m

$8 \times 8 \times 4(5)$ km

$SHF_s = (0.03, 0.06, 0.09, 0.12)$ [Km/s]

$EVP_s = 2.5\times10^{-5}$ [m/s]

Initial θ and q_t profiles – next slide

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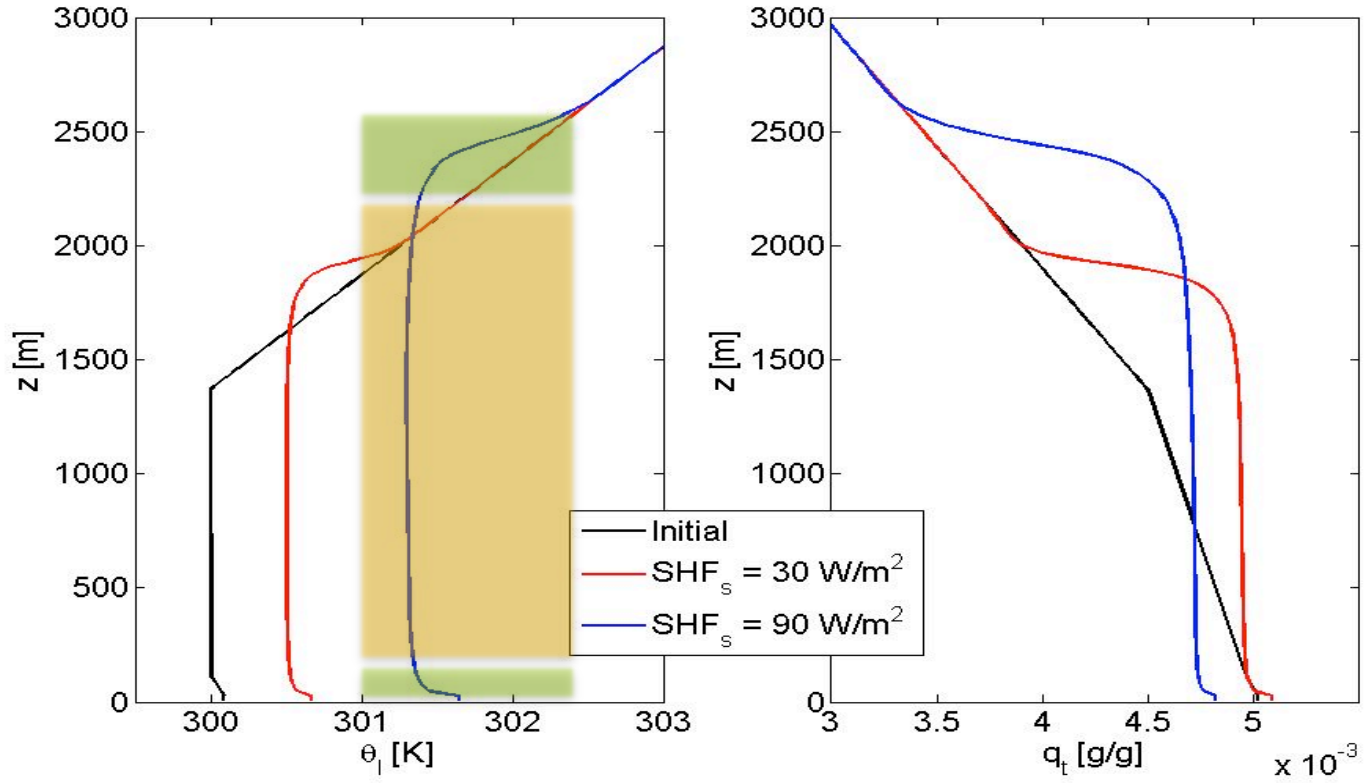
θ and q_t vertical profiles after 6 hours



Typical dry convective boundary layer structure:

- unstable surface layer,
- well mixed layer, and
- capping inversion

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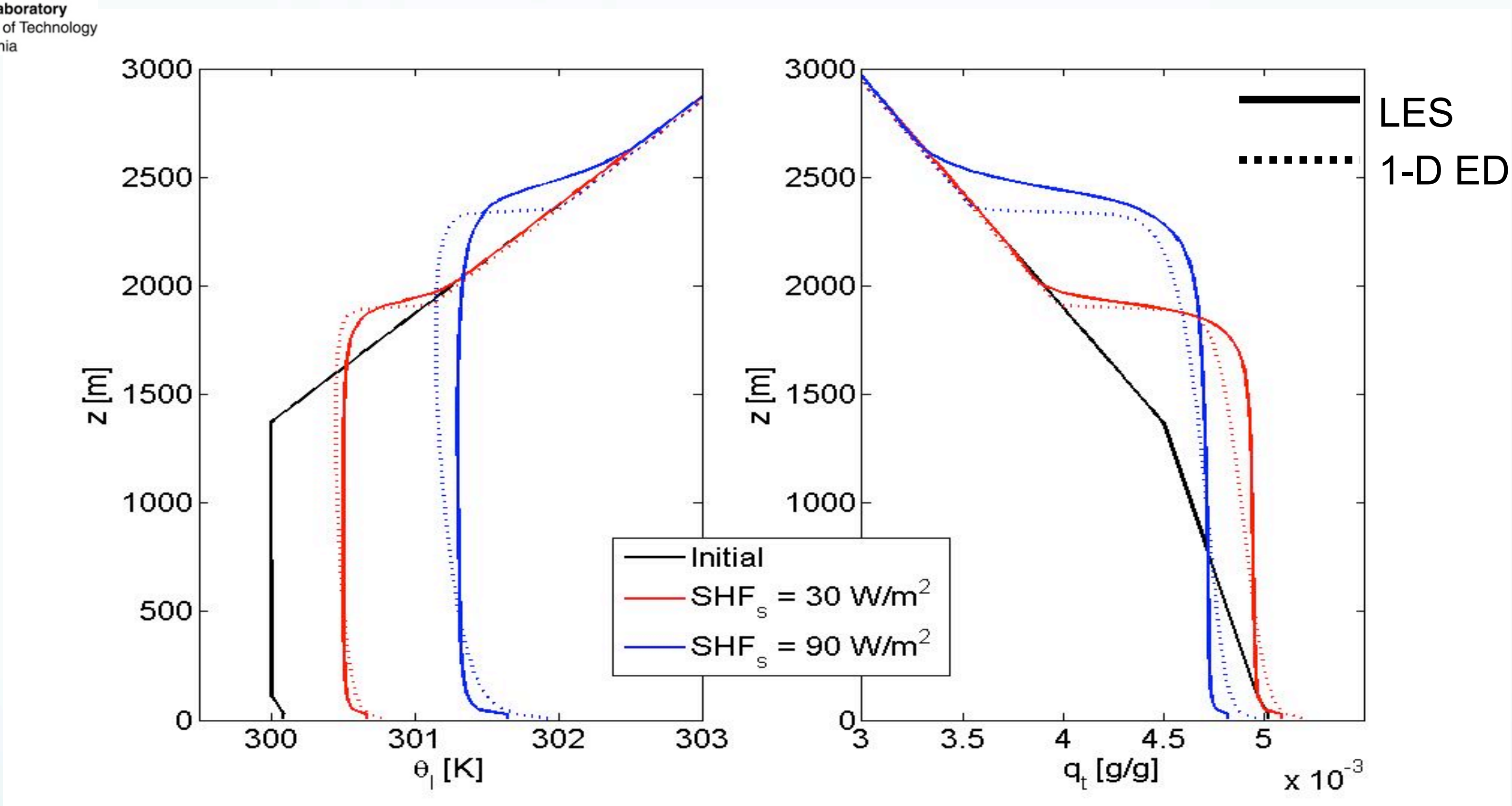
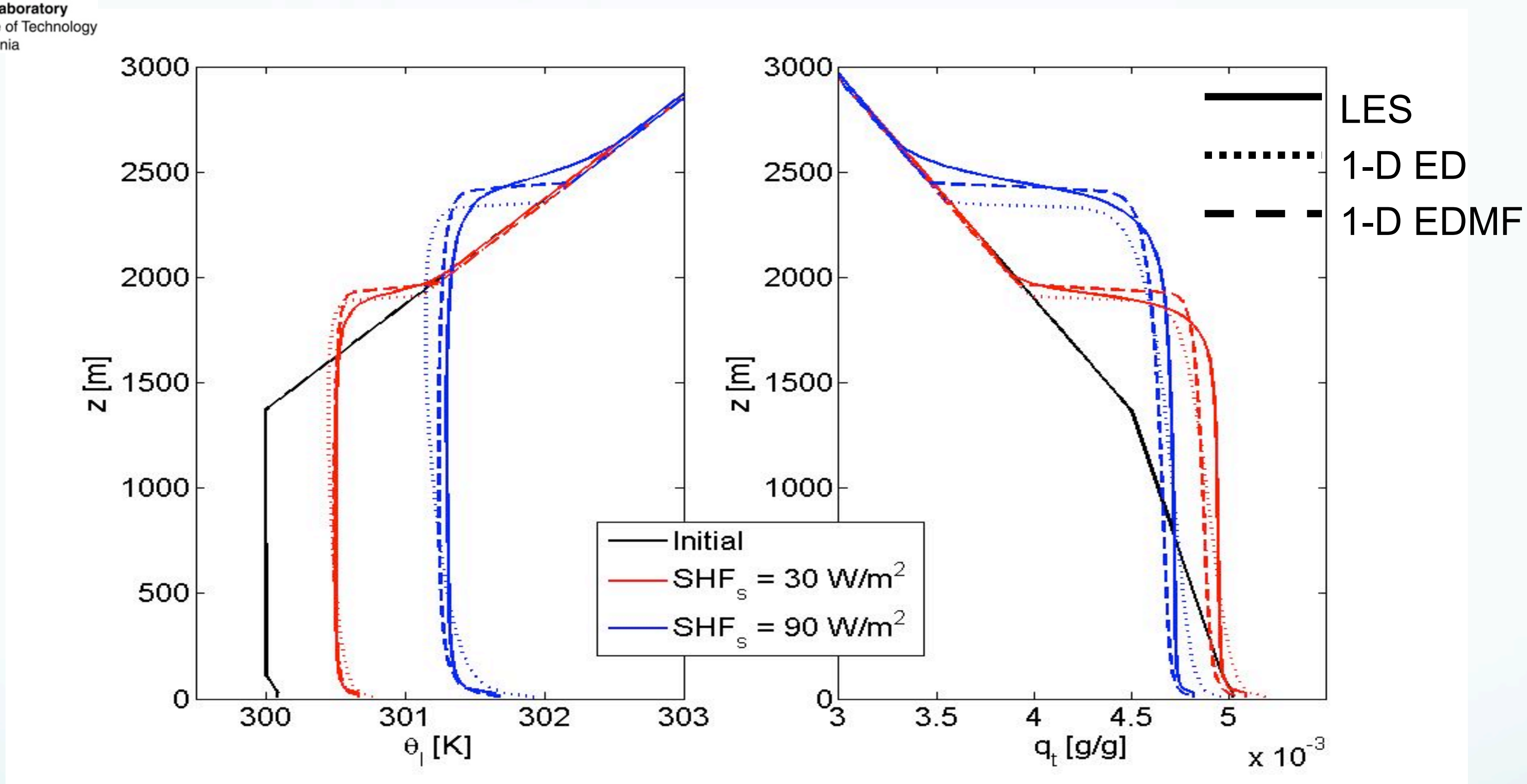
θ and q_t vertical profiles after 6 hours



Eddy-diffusivity simulations:

- the higher the surface heat flux the larger deviations from LES
- profiles not mixed well enough – unstable profile
- boundary layer too shallow
- surface profiles warmer than LES

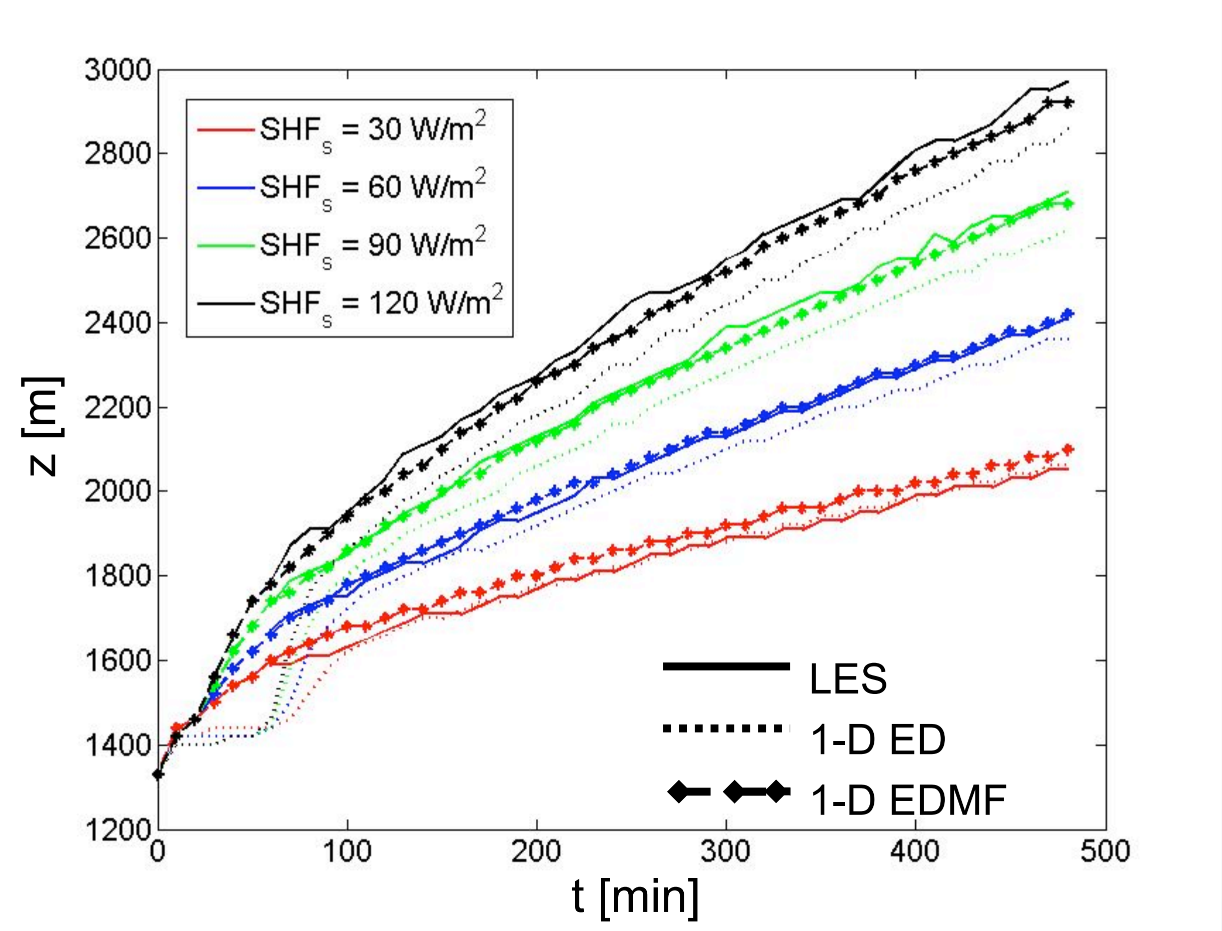
θ and q_t vertical profiles after 6 hours



Full EDMF simulations:

- surface layer more realistic
- neutral profile in the well-mixed layer
- larger entrainment leads to better inversion height
- inversion layer too sharp compared to LES

Boundary layer height evolution



Inclusion of the mass-flux term improves simulations of the boundary layer height for a variety of surface heat fluxes

Stratocumulus case

Moist physics

Prognostic equations for $\theta_L = \theta\left(1 - \frac{L_v}{T c_p} q_l\right)$ and $q_t = q_v + q_l$

PDF – based cloud parameterization (Cuijpers and Bechtold, 1995):

$$\begin{aligned} CC &= 0.5 + 0.36\,\mathrm{arctan}(1.55 Q_1) \\ q_l &= \sigma_s \begin{cases} e^{1.2 Q_1 - 1} & Q_1 < 0 \\ e^{-1} + 0.66 Q_1 + 0.086 Q_1^2 & Q_1 > 0 \end{cases} \end{aligned}$$

$$Q_1 = \frac{s}{\sigma_s}$$

s – saturation deficit

σ_s – standard deviation of *s*

$$\begin{aligned} s &= q_t - q_s(T) = \frac{1}{1+\gamma}\left(q_t - q_s(T_l)\right) \\ \sigma_s &= \max\left[l s \left(\left(a^2 \frac{\partial q_t}{\partial z} \right)^2 + \left(b^2 \frac{\partial \theta_L}{\partial z} \right)^2 - 2ab \frac{\partial \theta_L}{\partial z} \frac{\partial q_t}{\partial z} \right)^{1/2}, 1e-6 \right] \end{aligned}$$

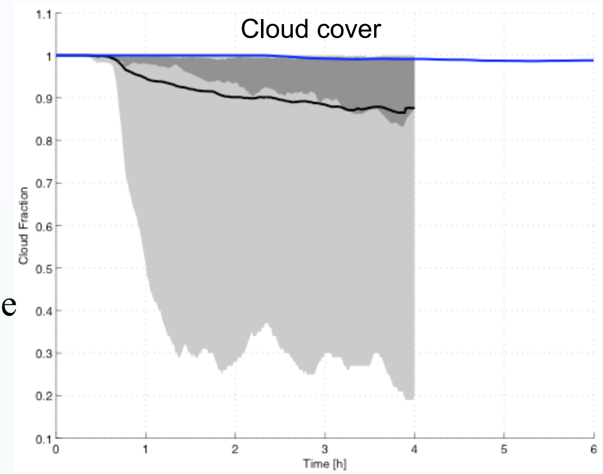
DYCOMS stratocumulus case study – 1-D simulations vs. LES results (Stevens et al., 2005)

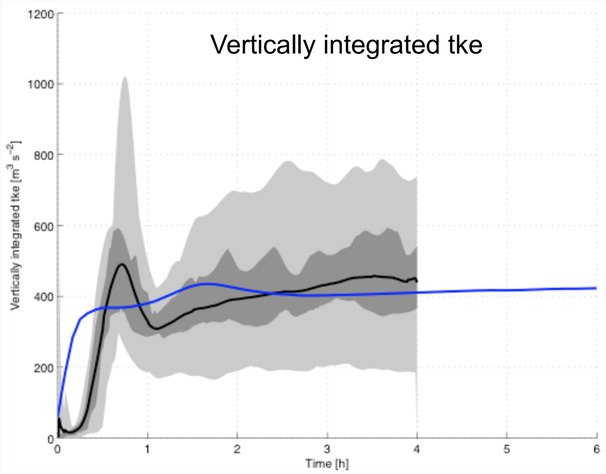
- Subtropical Pacific off-coast California
- Persistent cloud layer, homogeneous environmental conditions

Time series

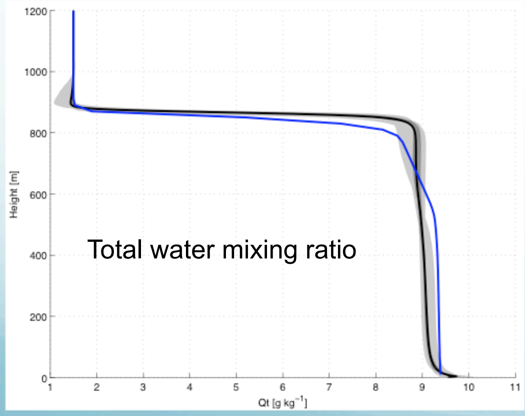
LES average

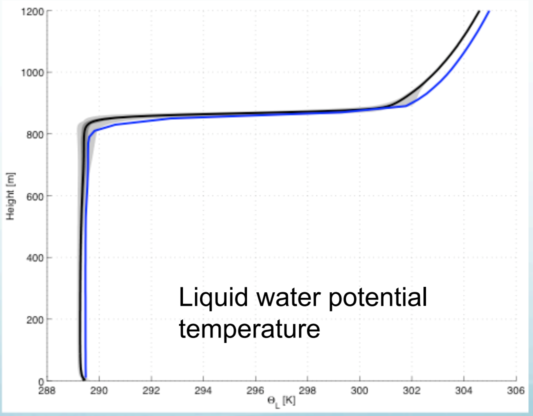
1-D sim.

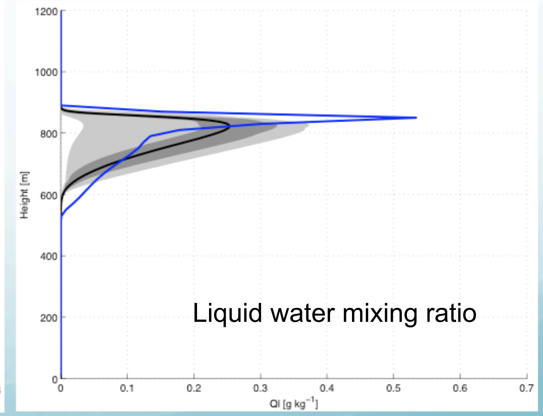




Vertical profiles averaged between 3rd and 4th simulation hour:







Conclusions and further plans

- EDMF improves 1D simulations of dry convective PBL's
- Stratocumulus simulations compare well with LES

Plans:

- test EDMF parameterization in the COAMPS mesoscale model
- investigate simulation of Sc-to-Cu transition with EDMF

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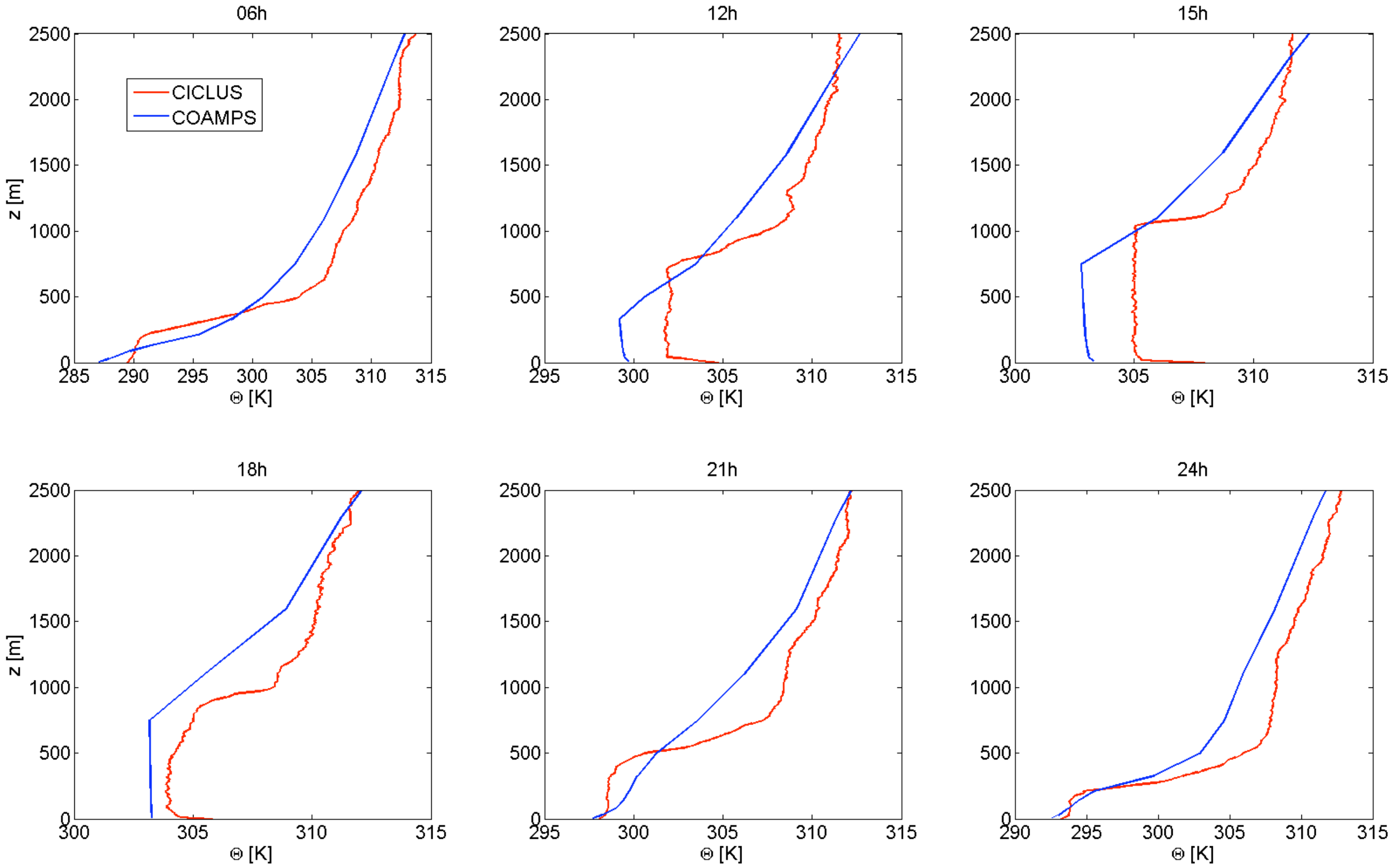

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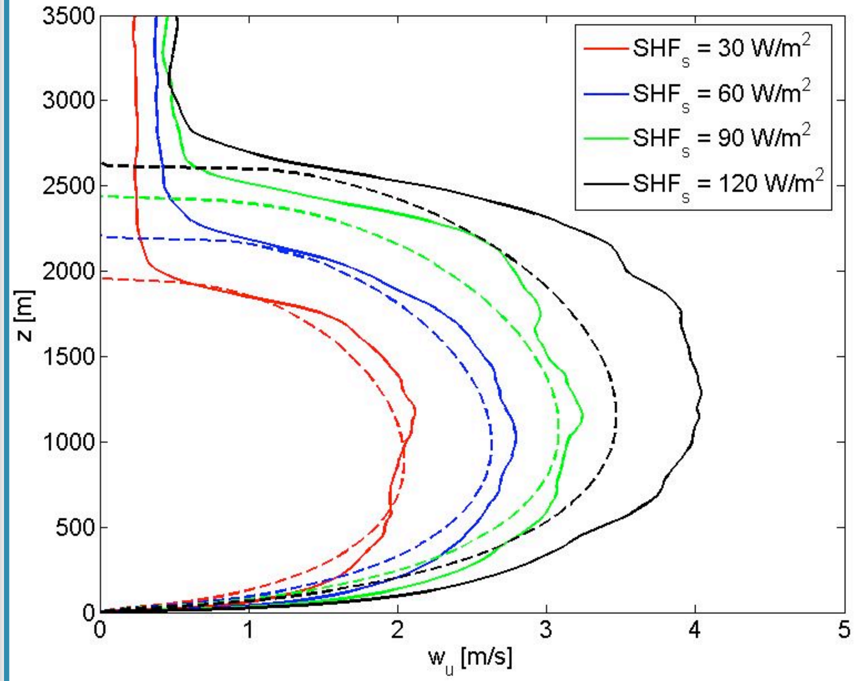
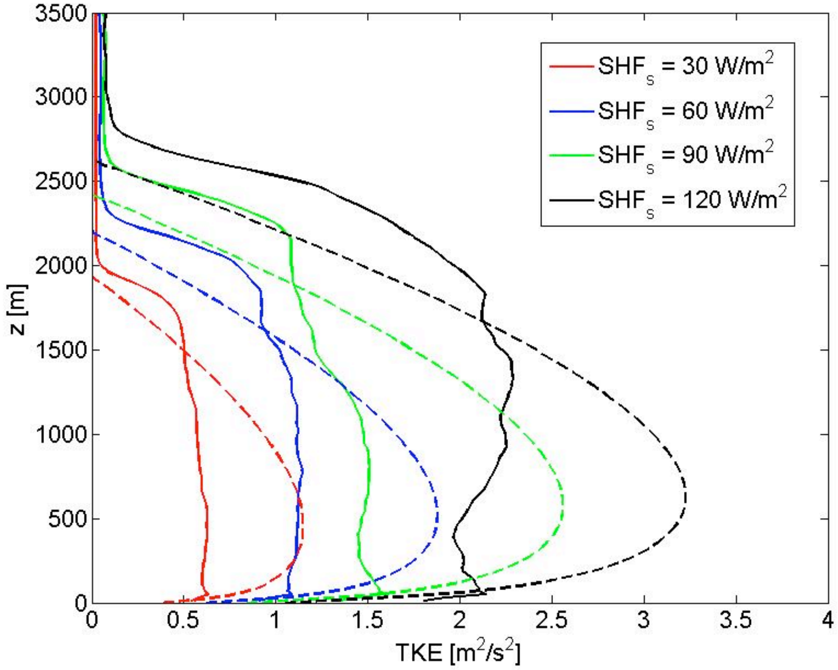
$$\frac{\partial \phi_u}{\partial z} = -\varepsilon\left(\phi_u - \bar{\phi}\right) \qquad \phi_{u,s} = \bar{\phi} + \beta \frac{\overline{w'\phi'}^s}{\sqrt{e_s}}, \quad \beta = 0.3$$

$$\frac{\partial w_u^2}{\partial z} = -\varepsilon_w b_1 w_u^2 + b_2 F_{w,u} \qquad F_{w,u} = g\left(\theta_{v,u} \big/ \overline{\theta}_v - 1 \right)$$





DYCOMS initial conditions: