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EDMF: shallow convection and transition to stratocumulus – a stochastic approach

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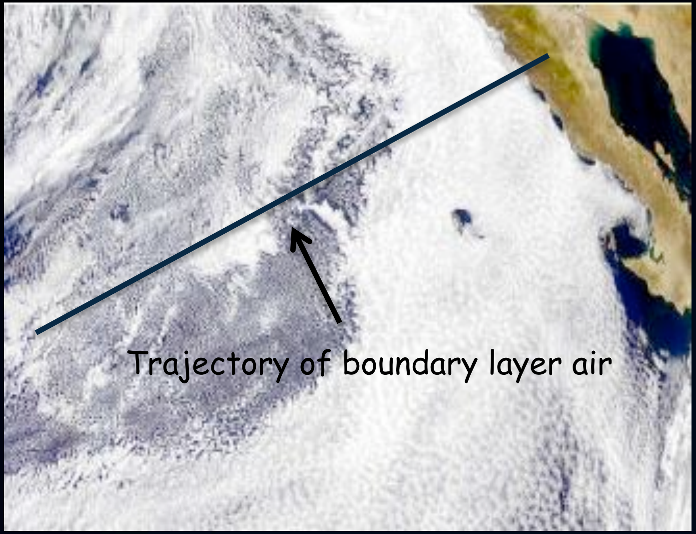
Improving physical parameterizations for global circulation models

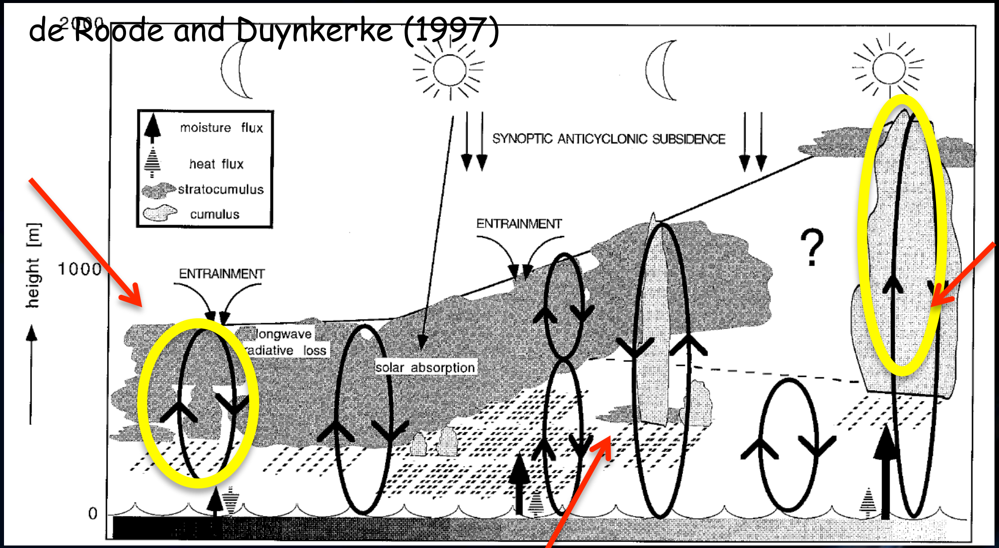
Main motivation - Improvement of simulation of stratocumulus, shallow cumulus and transition in global climate models

Strategy -developing physical parameterizations in single column model (SCM), evaluation with Large Eddy Simulation (LES) results



Stratocumulus to shallow cumulus transition off coast California

Stratocumulus - Mixed layer models (e.g. Stevens 2006)



Shallow cumulus - mass flux models (e.g. Neggers et al., 2006)

Transition mechanisms:

- Cloud top entrainment instability (Randall, 1980)
- Surface forced decoupling (Bretherton and Wyant, 1997)
- Microphysical processes (e.g. Jiang et al. 2002)

Physical processes influencing the formation and break up of the low level clouds:

- Large scale dynamics (Hadley-Ferrel circulation)
- Cloud physics
- Turbulence (boundary layer and convection)
- Radiation

Single column model

Simulation of non-precipitating moist convection

Prognostic equations for large scale flow:

Radiation flux

Horizontal advection

$$\frac{\partial \theta_L}{\partial t} = -w\frac{\partial \theta_L}{\partial z} - \vec{u_h}\nabla_h \theta_L - \frac{\partial \overline{w'\theta'_L}}{\partial z} - \frac{1}{\rho c_p}\frac{\partial R_f}{\partial z}$$

$$\theta_L = \theta - \frac{L_v}{c_p} q_l$$

$$\frac{\partial q_t}{\partial t} = -w\frac{\partial q_t}{\partial z} - \vec{u_h}\nabla_h q_t - \frac{\partial \overline{w' q'_t}}{\partial z}$$

$$q_t = q_v + q_l$$

$$\frac{\partial u}{\partial t} = -w\frac{\partial u}{\partial z} - \vec{u_h}\nabla_h u - \frac{\partial \overline{w' u'}}{\partial z} + f(v - v_g)$$

$$\frac{\partial v}{\partial t} = -w\frac{\partial v}{\partial z} - \vec{u_h}\nabla_h v - \frac{\partial \overline{w' v'}}{\partial z} - f(u - u_g)$$

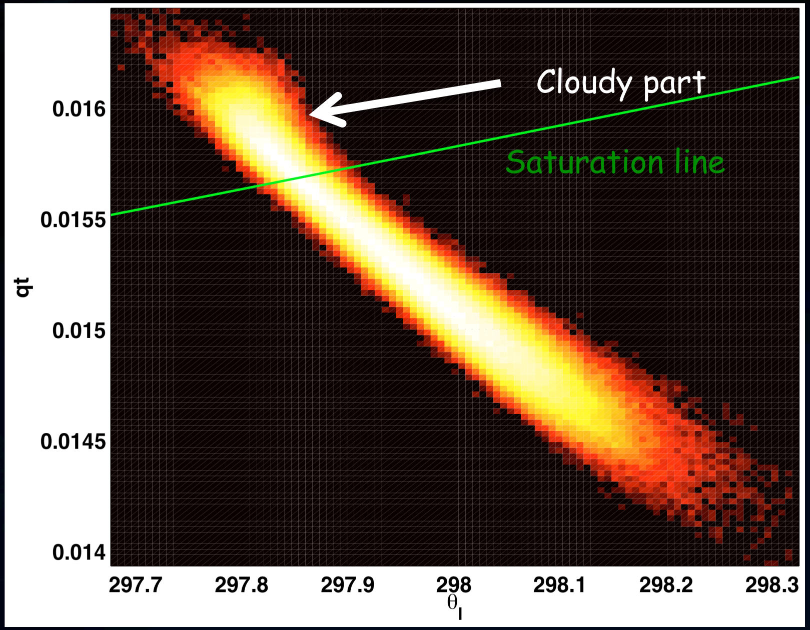
Geostrophic
wind components

Subsidence
(large scale flow)

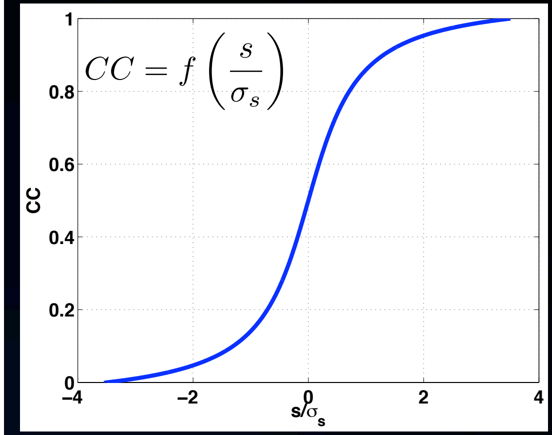
Turbulent fluxes
(boundary layer + convection)

Condensation and radiation parameterizations

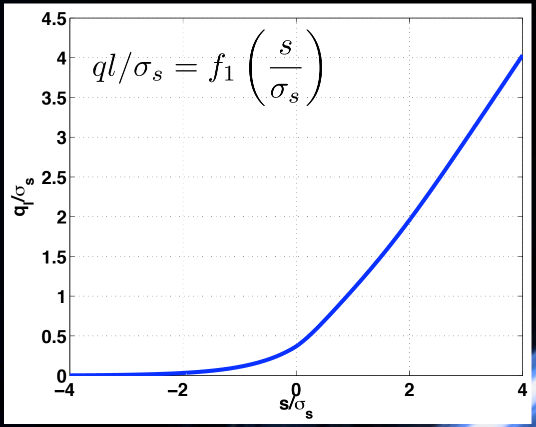
Cloud physics – *pdf* scheme (e.g. Cheinet and Teixeira, 2003)



2D pdf of Θ_L [K] and q_T [kg/kg] at cloud base for shallow cumulus (RICO) case – from LES



$$s = q_t - q_s(p, \theta_L)$$



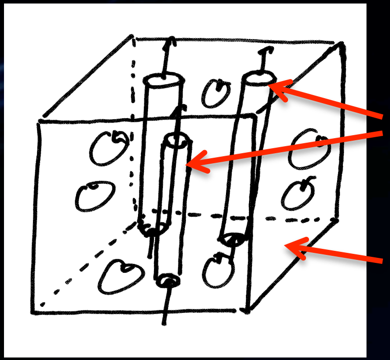
Radiation Scheme – long-wave for cloudy layers only

- maximum cloud overlap
- emissivity based on liquid water content

Key for coupling between condensation and turbulence:

- Buoyancy flux
- Radiation (long-wave only)

EDMF: turbulent parameterization and beyond



Current scheme:

- Parameterization of turbulent fluxes (EDMF)

Future plans – estimation of joint *pdf(*Θ_L, q_t, w*)*:

- Condensation and moist physics
- Transport of e.g. pollutants (transport α w^a)

$$\overline{w'\varphi'} = \underbrace{\overline{w'\varphi'}|_{ed}} + \underbrace{\sum_j a_j(w_j - w_e)(\varphi_j - \varphi_e)}$$

environment

thermals

Local mixing 'eddy-diffusivity' (ε-l scheme):

$$\overline{w'\varphi'}|_{ed} = -K\frac{\partial\varphi}{\partial z}$$

$$K = Cl\sqrt{e}$$

Turbulent kinetic energy

$$l = l(kz, \tau\sqrt{e}, \sqrt{e}/N)$$

Turbulent length scale

Mass-flux parameterization – bulk thermals (only for θ_L and q_t):

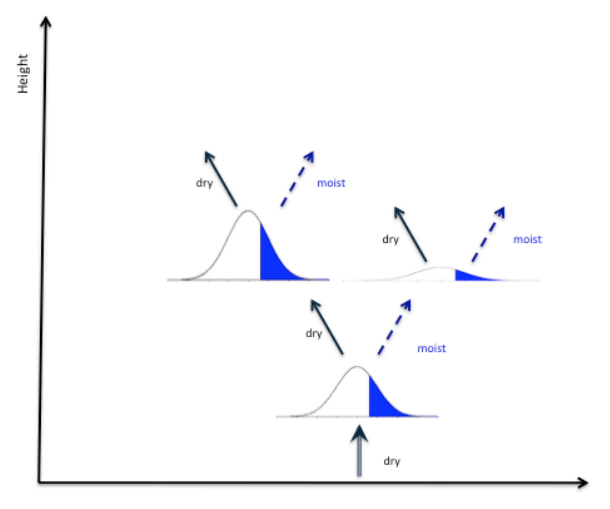
Entrainment coefficient

$$\frac{\partial\varphi_j}{\partial z} = \epsilon_j(\varphi_e - \varphi_j) \quad \varphi = \theta_L, q_t$$

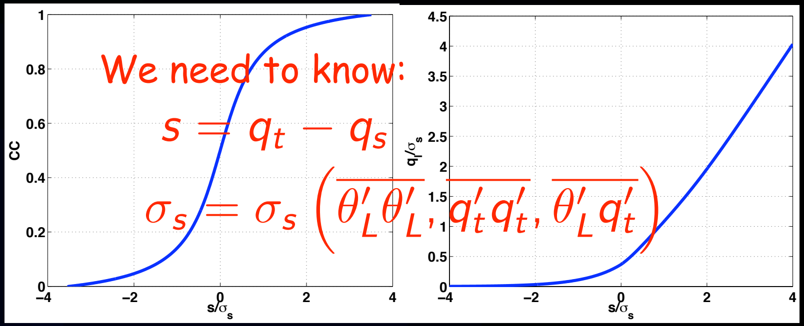
$$\frac{1}{2}\frac{\partial w_j^2}{\partial z} = ag\left(\frac{\theta_{vj}}{\theta_{ve}} - 1\right) - (b + c\epsilon_j)w_j^2$$

Constants

1. pdf based mass/flux parameterization



Condensation scheme – moist/dry updraft area (Cheinet & Teixeira, 2003):



We need to know:

$$s = q_t - q_s$$

$$\sigma_s = \sigma_s\left(\overline{\theta'_L\theta'_L}, \overline{q'_t q'_t}, \overline{\theta'_L q'_t}\right)$$

Estimation of covariance within updraft:

$$2\overline{w'\varphi'_u}\frac{\partial\varphi_u}{\partial z} = \epsilon_{\varphi_u} \longrightarrow \overline{\varphi'_u\varphi'_u} = \frac{3}{2}\frac{\tau_u^2}{C}w_u^2\varepsilon^2\left(\varphi_u - \varphi\right)^2, \ \varphi_u = \theta_L, q_t$$

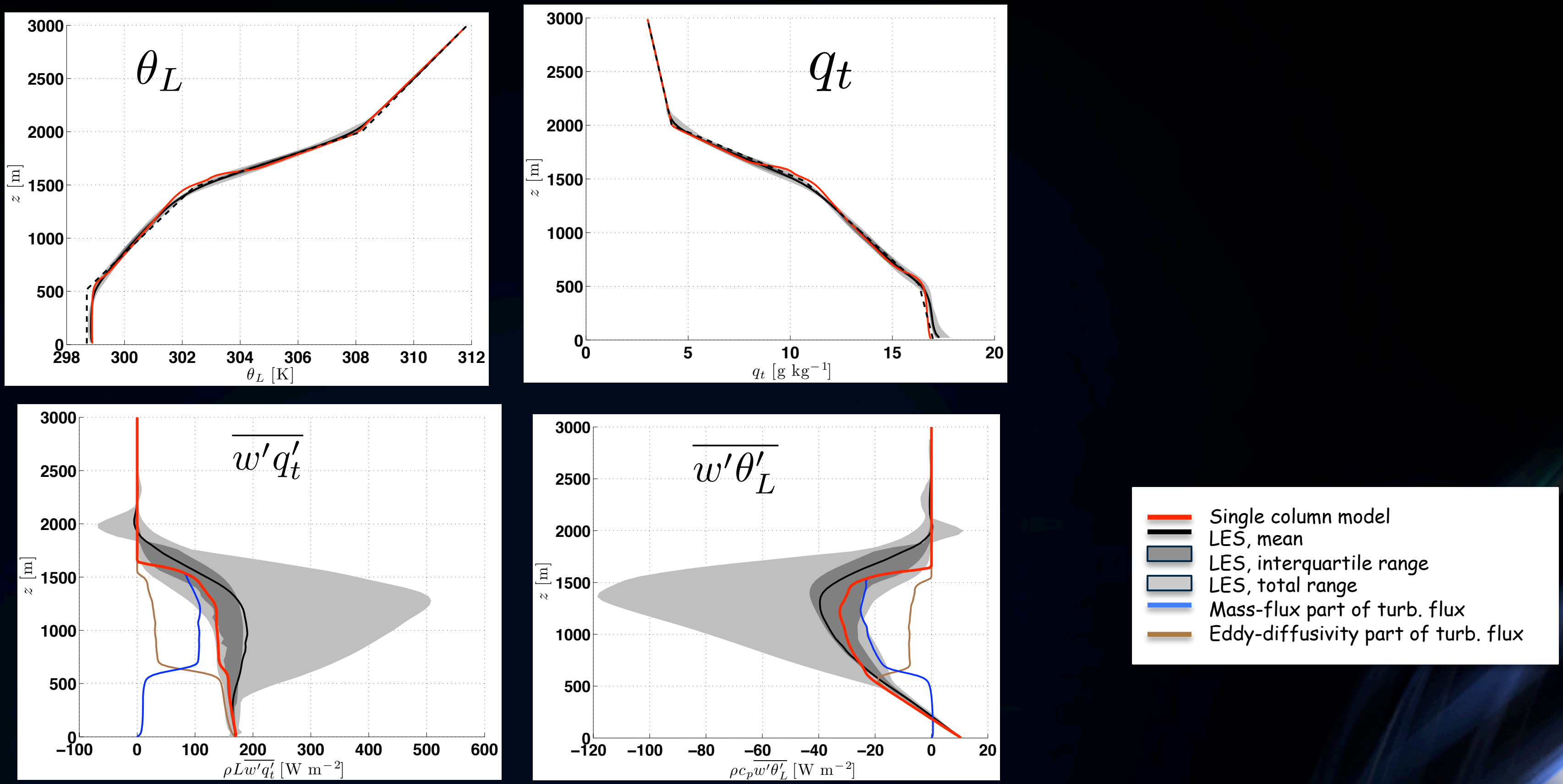
$$\overline{\theta'_L q'_t} = -0.7\sqrt{\overline{\theta'_L\theta'_L}\cdot\overline{q'_t q'_t}}$$

Updraft scheme:

- Start with a single dry updraft at surface, integration in vertical
- Estimation of cloud cover and liquid water at each vertical level (pdf cloud scheme of Cheinet and Teixeira 2003)
- Separation of dry and dry updraft if condensation occurs, each of the updrafts is integrated independently
- Entrainment rate ε=1/τw

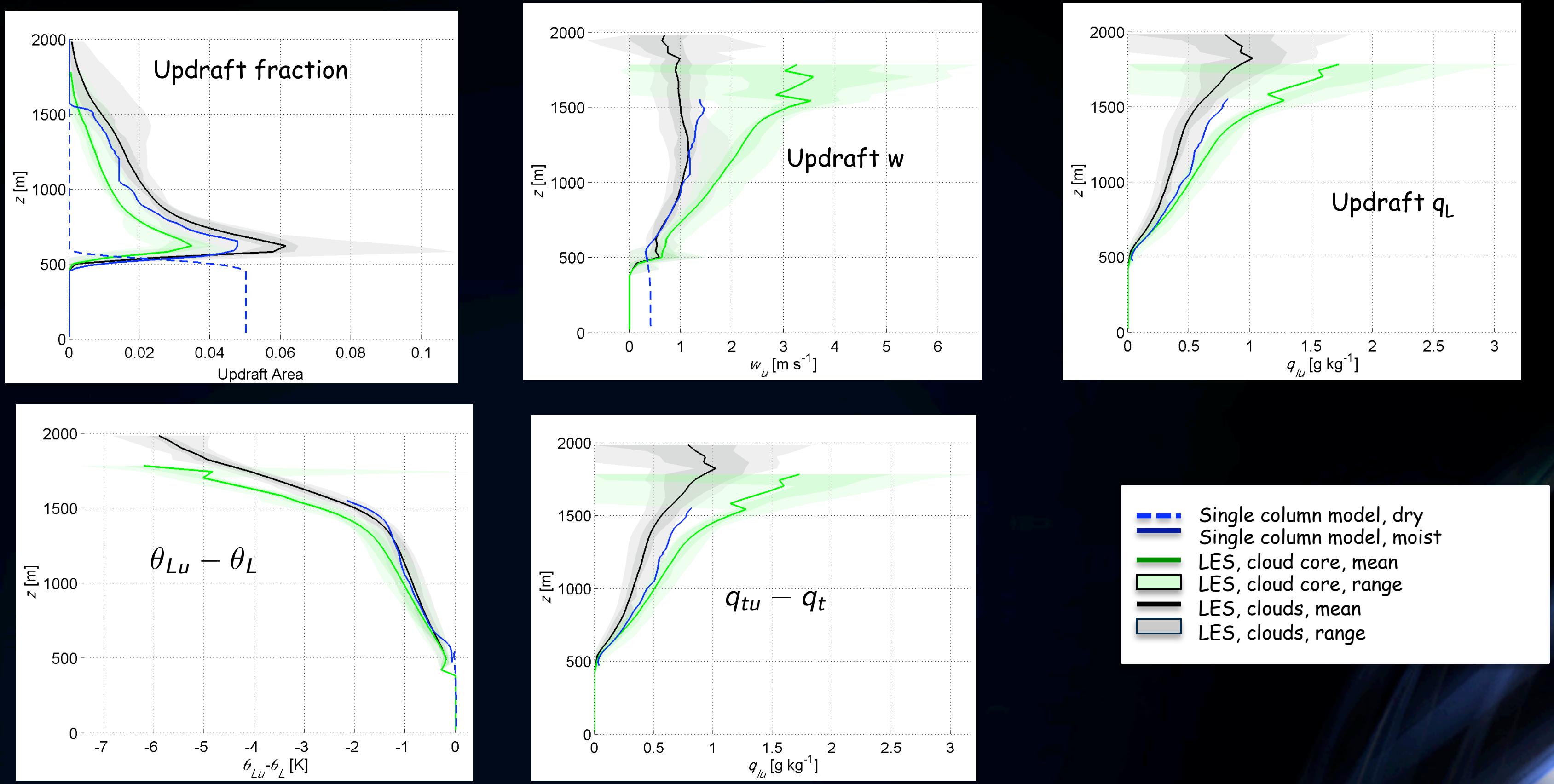
Results – Shallow cumulus case

BOMEX case, comparison with LES results from Siebesma et al. (2003)



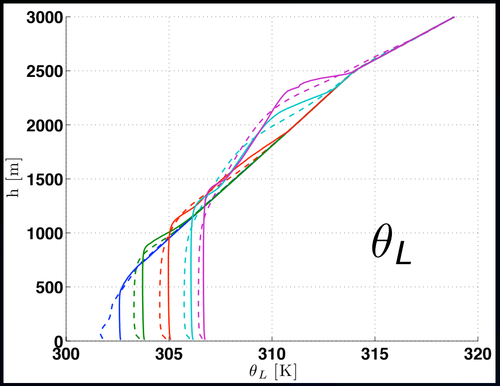
Results – Shallow cumulus case, cont. (moist thermals)

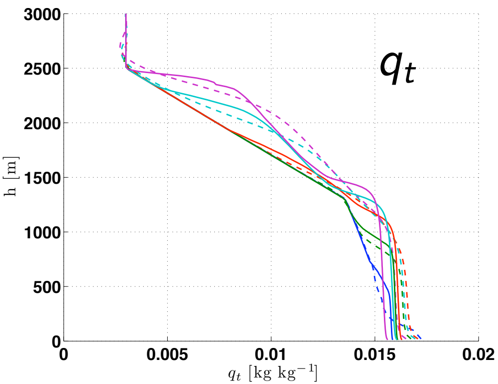
BOMEX case, comparison with LES results from Siebesma et al. (2003)

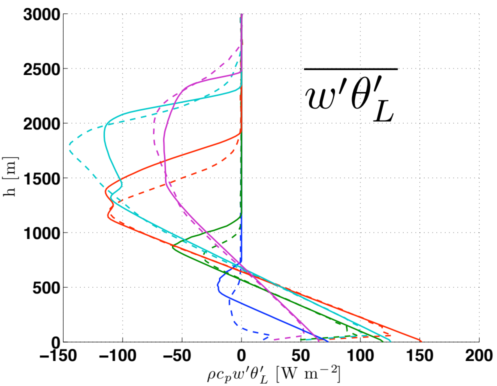


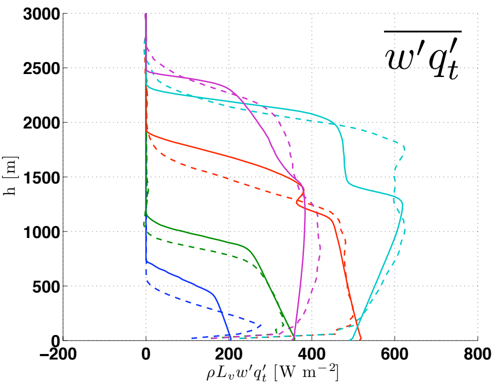
Results – ARM case

ARM case, comparison with LES simulations

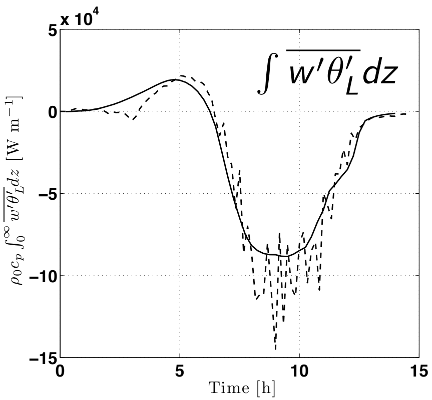


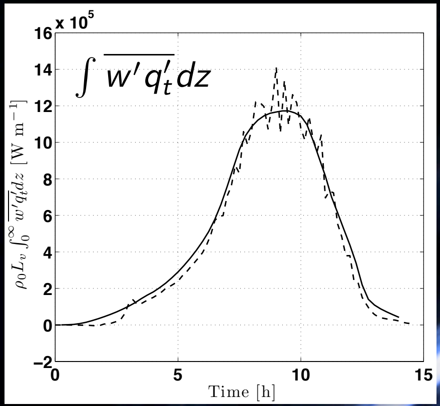






Full line - SCM
Dashed line - LES
Profiles drawn every third hour





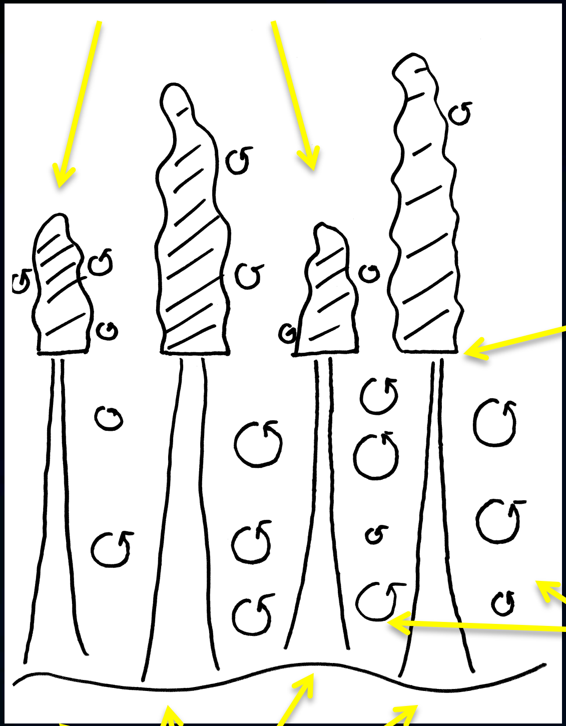
2. Stochastic mass flux parameterization

Problems with pdf based scheme:

- Number of updrafts not well controlled
- Updrafts do not reach level of neutral buoyancy
- High sensitivity on entrainment rate (1/τw)

Observations

Cumulus clouds with different cloud-top



Well defined cloud base

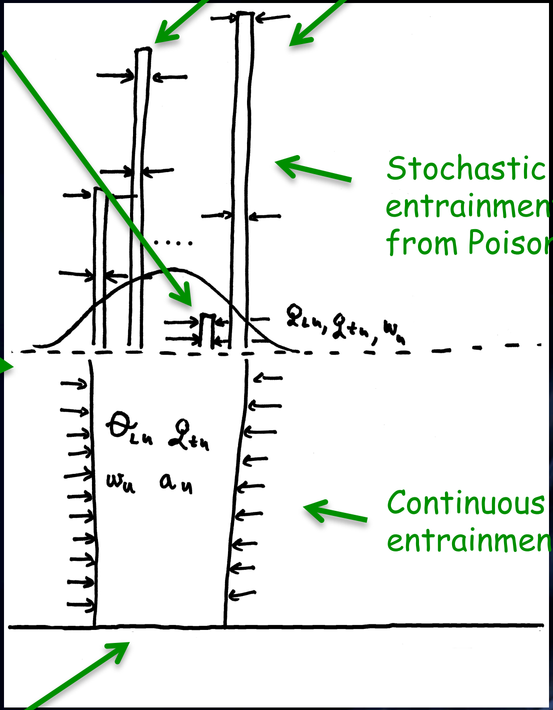
Small scale 'eddy diffusivity' turbulence

Dry updrafts – cumulus 'roots'

Updraft model

More entrainment events per height - lower height

Less entrainment events per height - higher height



Condensation level -bulk updraft split into N (N=10) updrafts, properties drawn from joint normal *pdf* of Θ_L, q_t, w

Stochastic discrete entrainment rate – drawn from Poison distribution

Continuous and constant entrainment rate

Single bulk updraft initiated at surface

Mass flux parameterization, a few details

Entrainment rate

Below condensation level:
- Fixed entrainment rate

Above condensation level:
- Stochastic, discrete event*
- Each entrainment event entrains fixed amount of mass (20% of its mass)
- For updraft traversing distance *dz* , probability of entrainment event equals to *dz/L₀* (on average 10 updraft events between the updraft condensation and level of neutral buoyancy, finite Δz -> Poisson distribution of entrainment)

(*Inspired by Romps and Kuang, 2010)

Updraft area at surface

- Constant (4% of the area)

Estimation of cloud base joint *pdf*(Θ_L, q_t, w) within updraft:

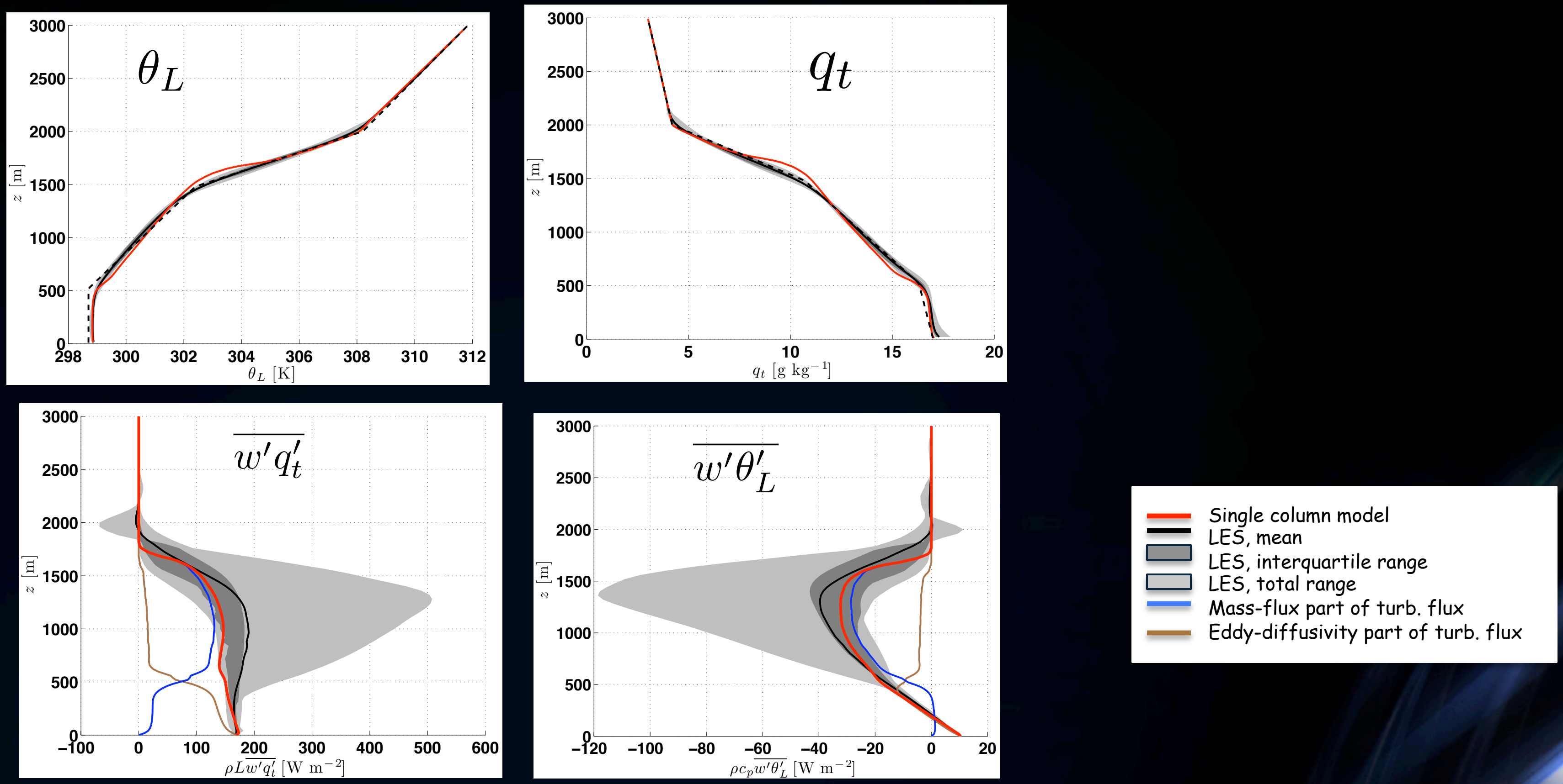
$$
\begin{aligned}
\overline{\varphi'_u\varphi'_u} &= \frac{3}{2}\frac{\tau_u^2}{C} w_u^2\varepsilon^2\left(\varphi_u-\varphi\right)^2,\ \ \varphi_u=\theta_L, q_t \\
\overline{w'_u w'_u} &= \frac{1}{2} w_u^2 \\
\overline{q'_{tu} w'_u} &= 0 \\
\overline{\theta'_{Lu} w'_u} &= 0.6\left(\overline{\theta'_{Lu}\theta'_{Lu}}\cdot\overline{q'_{tu}q'_{tu}}\right) \\
\overline{\theta'_{Lu} q'_t} &= 0.7\left(\overline{\theta'_{Lu}\theta'_{Lu}}\cdot\overline{q'_{tu}q'_{tu}}\right)\mathrm{sign}((\theta_{Lu}-\theta_L)(q_{tu}-q_t))
\end{aligned}
$$

Local balance between production and dissipation of second moments for conserved variables

Prescribed correlation coefficients

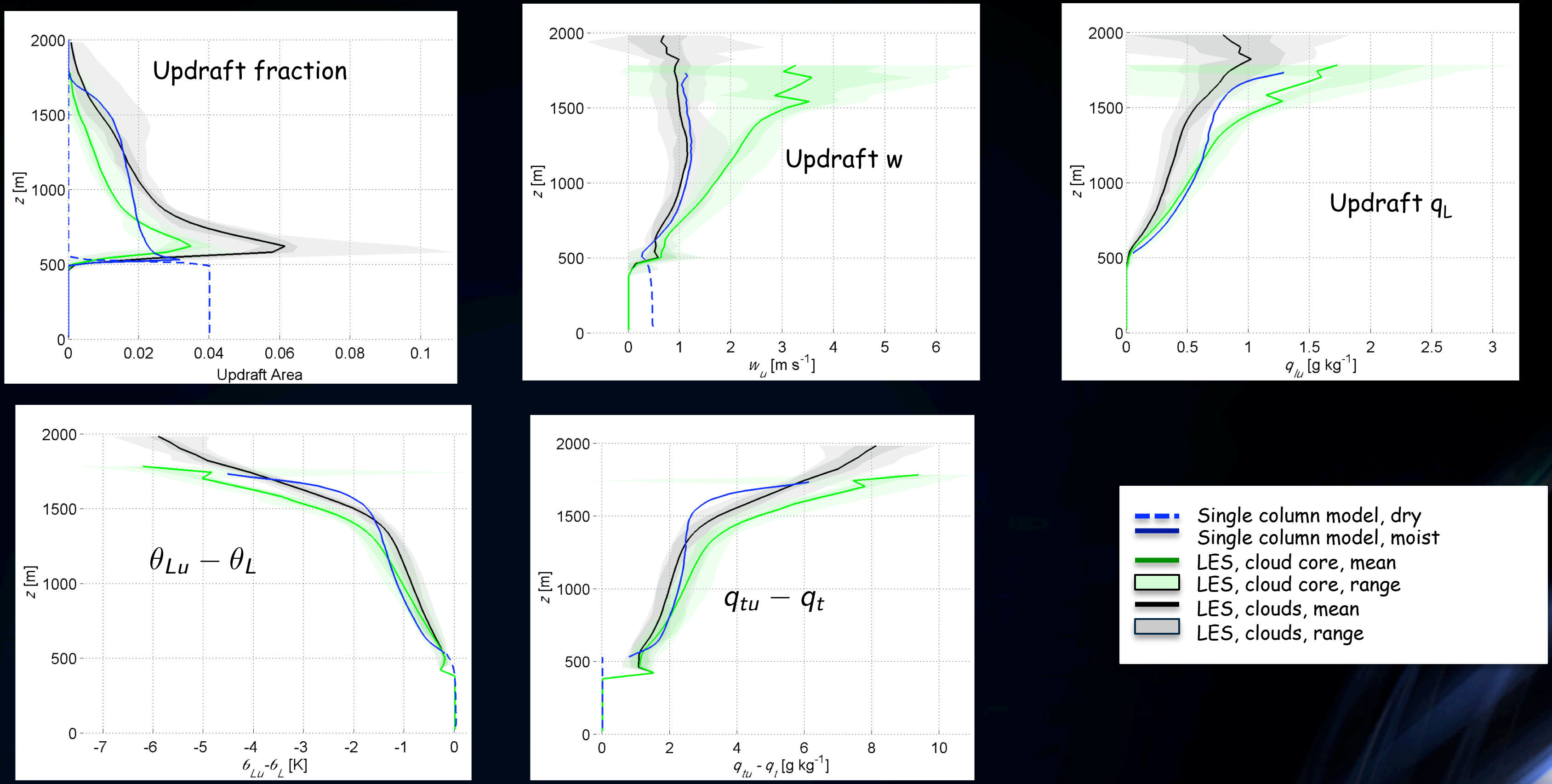
Results – Shallow cumulus case

BOMEX case, comparison with LES results from Siebesma et al. (2003)



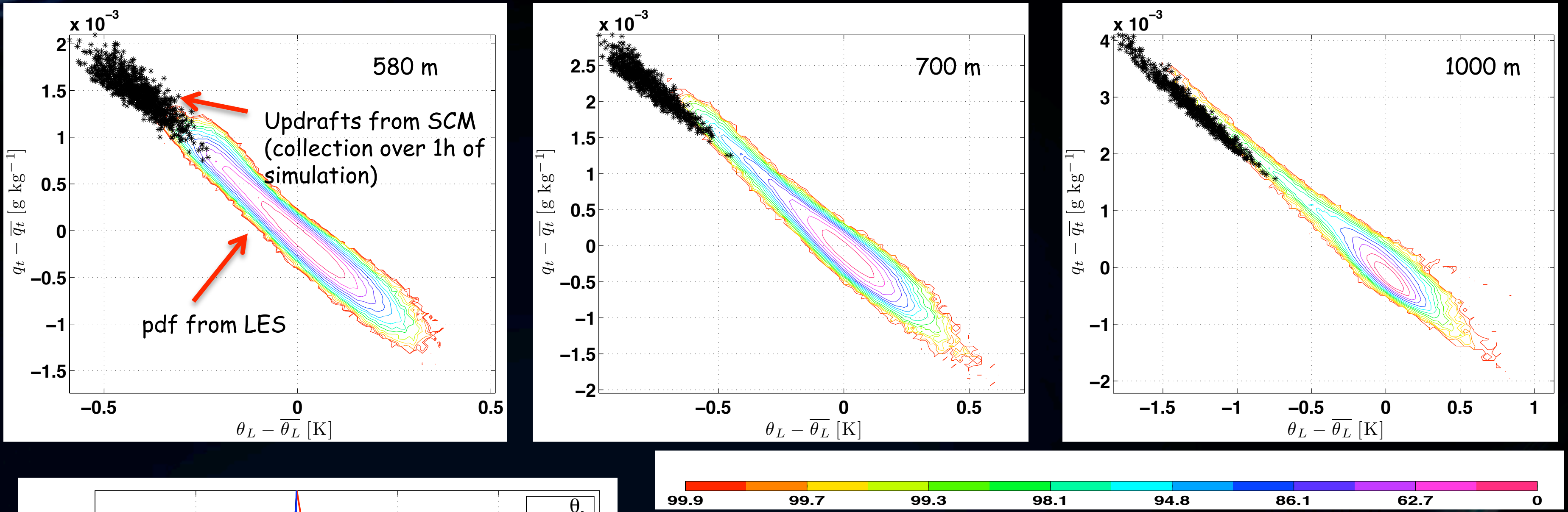
Results – Shallow cumulus case, cont. (moist thermals)

BOMEX case, comparison with LES results from Siebesma et al. (2003)



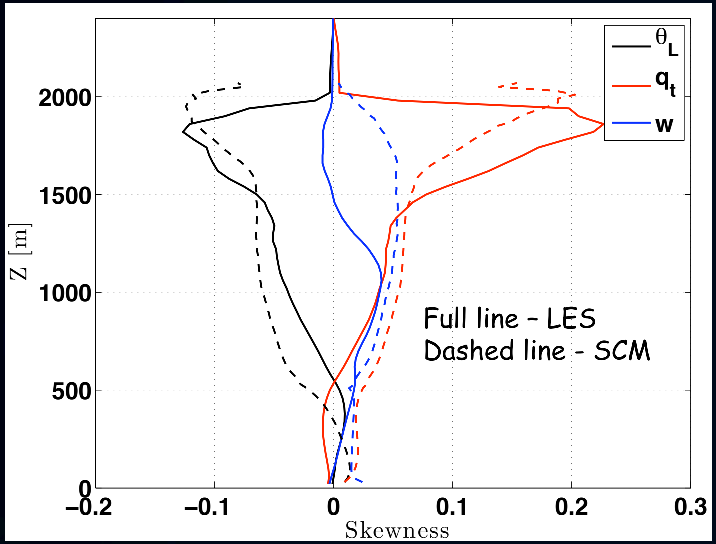
Results – Shallow cumulus case, cont.

Look into the joint *pdfs* of conserved variables and skewness, comparison between LES and updrafts



Updrafts from SCM (collection over 1h of simulation)

pdf from LES



Full line - LES
Dashed line - SCM

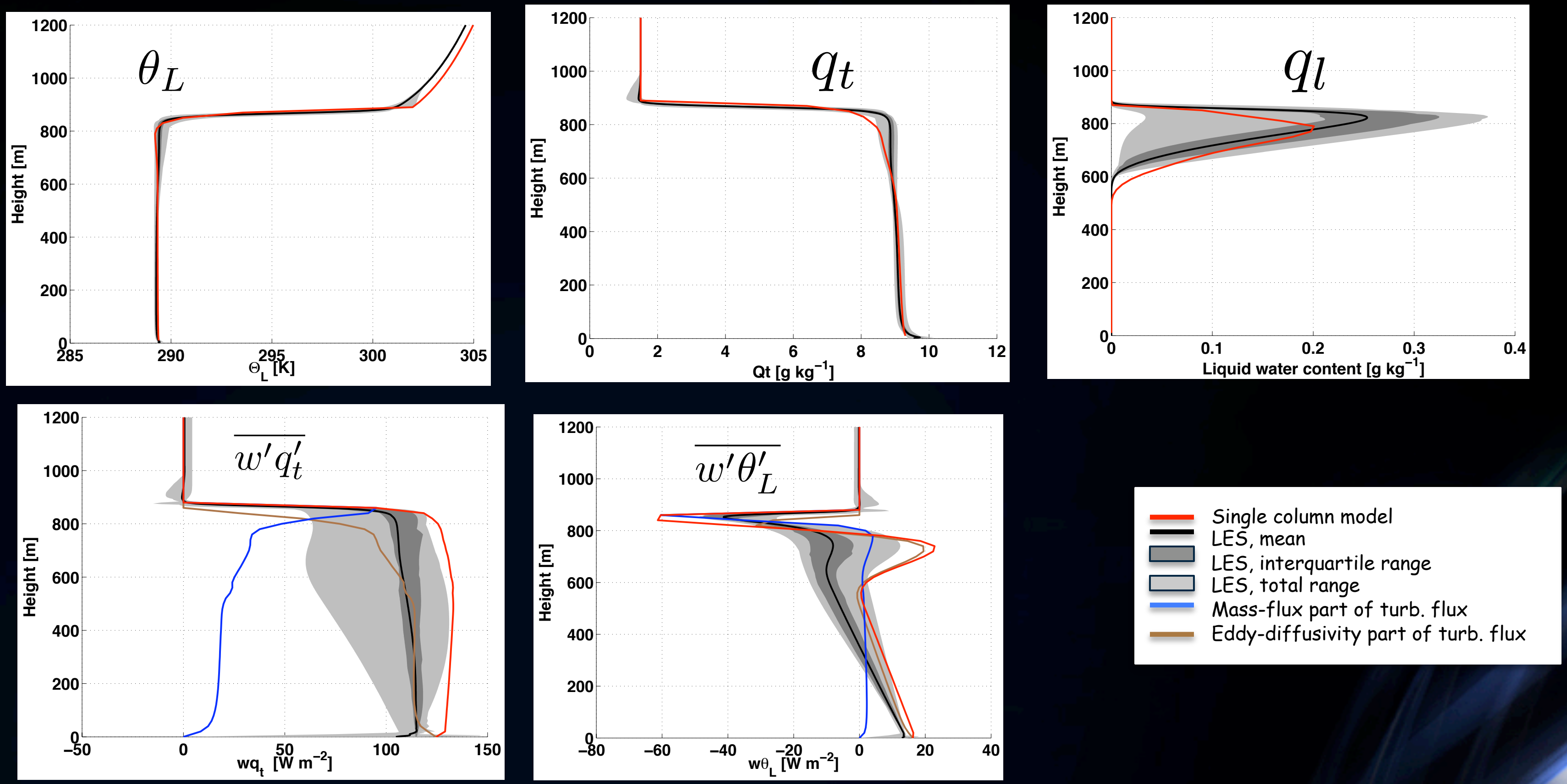
Estimation of skewness from LES:

- Only mass-flux contribute to skewness (eddy-diffusivity contribute to symmetric variability around mean)
- Second moment estimated from LES

$$Sk = \frac{\frac{1}{T}\sum_{t=1}^{T}\left(\sum_{n=1}^{N} a_i \left(\varphi_i - \overline{\varphi_i}\right)^3\right)^{1/3}}{std_\varphi} \qquad \varphi = \{\theta_L, q_t, w\}$$

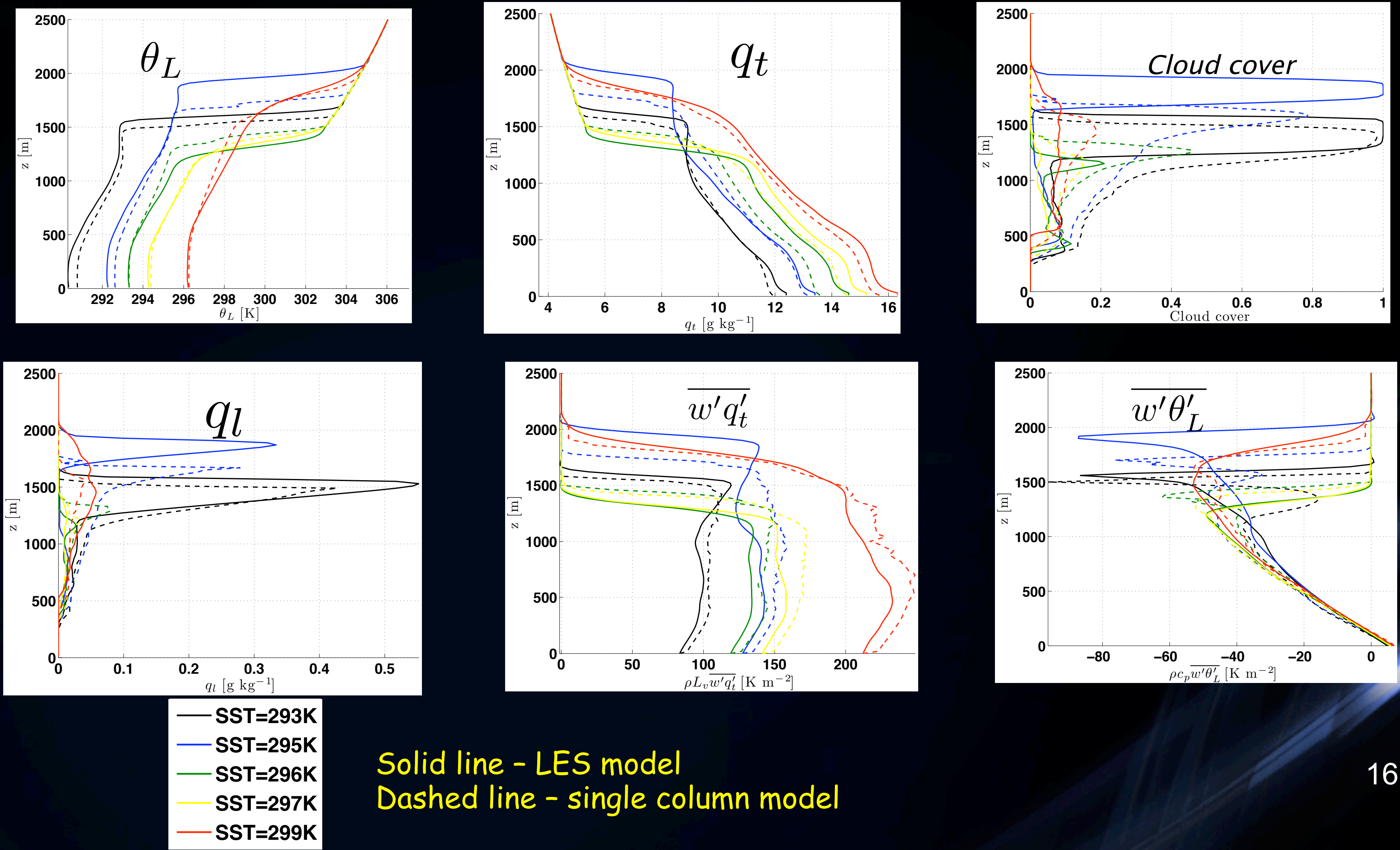
Results – Stratocumulus case

Simulation of DYCOMS-II case,
comparison with LES results from Stevens et al. (2005)



Results – Sc and Cu simulation

Simulation of ASTEX (stratocumulus) campaign results:
-4 simulations – 1 original, 4 with increased SSTs
-Comparison of stationary results from SCM with LES (Chung & Teixiera, 2011)



Solid line – LES model
Dashed line – single column model

Conclusions and further plans

- Combination of eddy-diffusivity and mass-flux is a promising parameterization approach for convective boundary layers
- We have successfully simulated the following cases: Stratocumulus, Cumulus, Transition from Sc to Cu, Dry convection

- Implementation and testing in full 3d model (NASA GEOS5)
- Proper coupling to other parameterizations
- Extension to precipitating convection