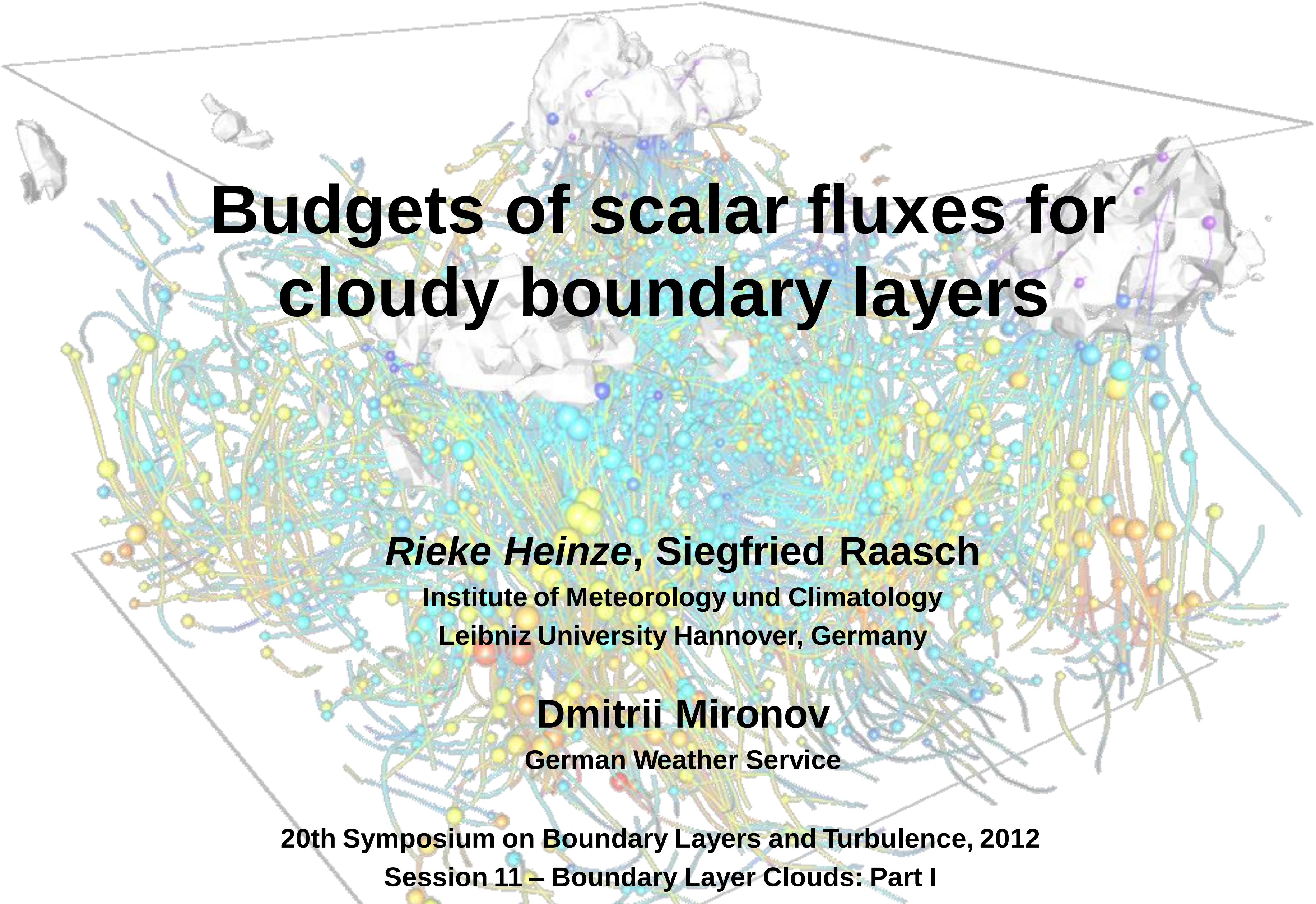

Budgets of scalar fluxes for cloudy boundary layers

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Session 11 – Boundary Layer Clouds: Part I

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- Turbulence closure models: most are based on truncated ensemble-mean budgets of second-moments
- So far: lack of comprehensive analysis for cloudy boundary layers

How do the scalar flux budgets look like?

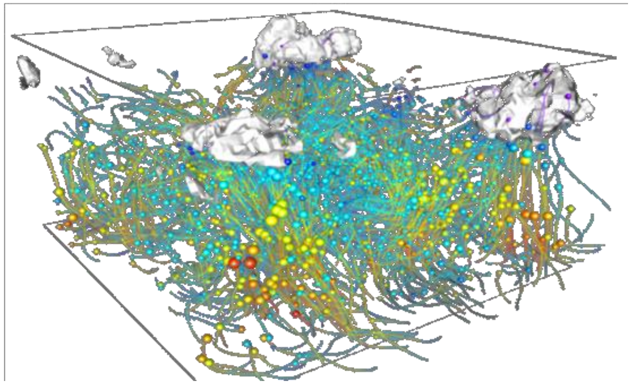
- Method: large-eddy simulation (LES)
- Parameterization of pressure-scalar and pressure-velocity covariances is the key issue in second-order modeling

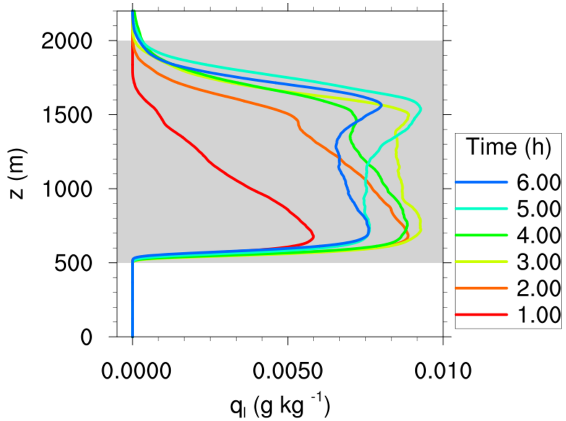
How do parameterizations of pressure-scalar covariance behave for cloudy boundary layers?

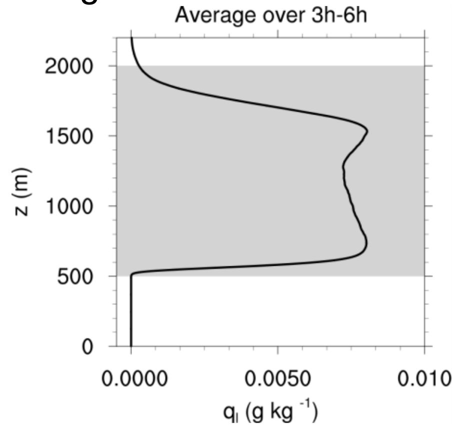
Method and setups

- Approximation to ensemble-mean budgets with LES:

horizontal average temporal average

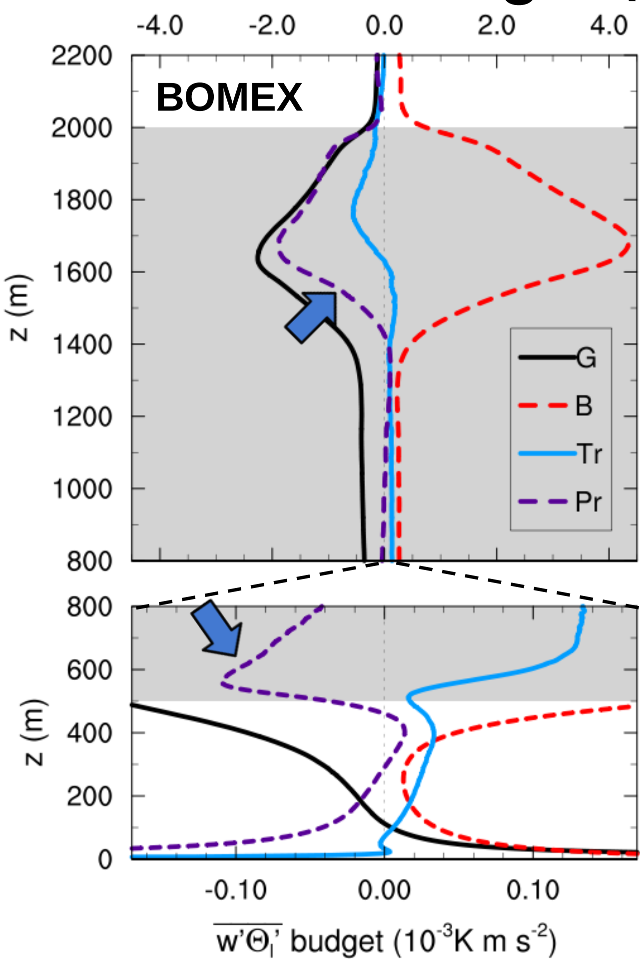






- Explicit consideration of sub-grid scale budgets → small residuals
- Simulations with PALM (palm.muk.uni-hannover.de)
  - Trade wind cumulus (BOMEX, Siebesma et al. 2003)
  - Nocturnal stratocumulus (DYCOMS-II (RF01), Stevens at al. 2005)

Scalar flux budget (s = liquid water potential temperature)



$$\frac{\partial}{\partial t}\overline{w'\theta_l'} = \boxed{-\overline{w'^2}\frac{\partial\overline{\theta_l}}{\partial z}}$$

mean gradient

$$+\frac{g}{\theta_0}\overline{\theta_l'\theta_v'}$$

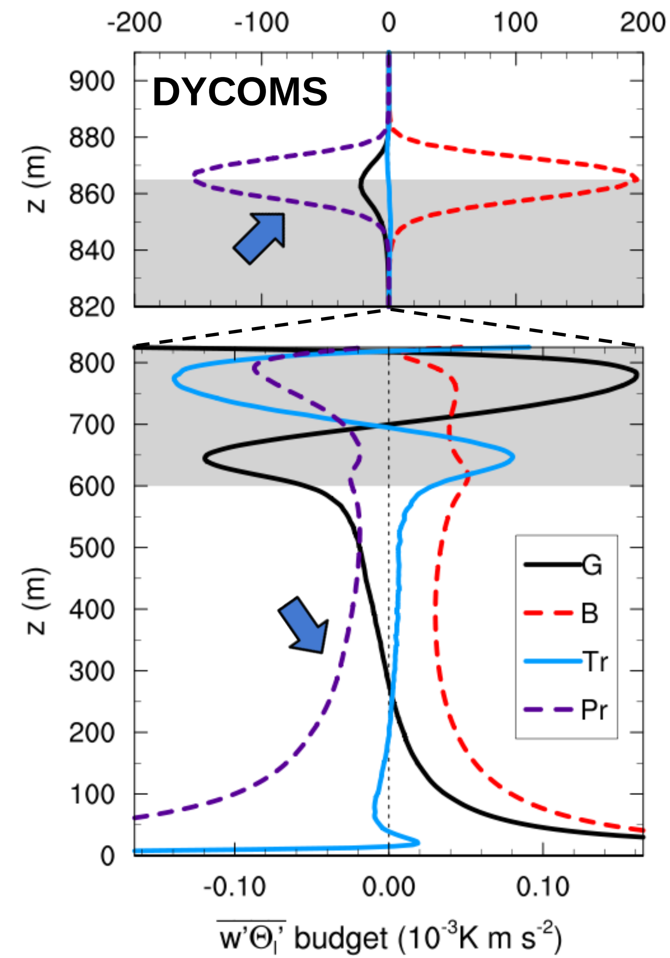
buoyancy

$$-\frac{\partial}{\partial z}\overline{w'^2\theta_l'}$$

transport

$$-\frac{1}{\rho_0}\overline{\theta_l'\frac{\partial p'}{\partial z}}$$

pressure term

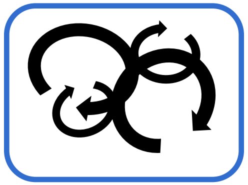


⇒ Dominated by mean-gradient (G), buoyancy (B) and pressure-term (Pr)

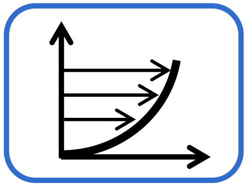
Modeling approach

- First tested for slightly sheared CBL (Moeng and Wyngaard 1986)

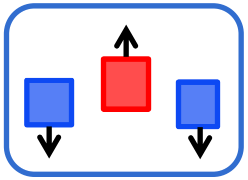
$$\boxed{\Pi_{si} = \frac{1}{\rho_0} \overline{s' \frac{\partial p'}{\partial x_i}}}$$



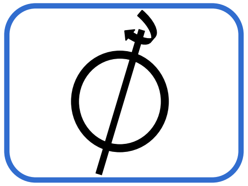
turbulence T



mean shear S



buoyancy B



Coriolis C

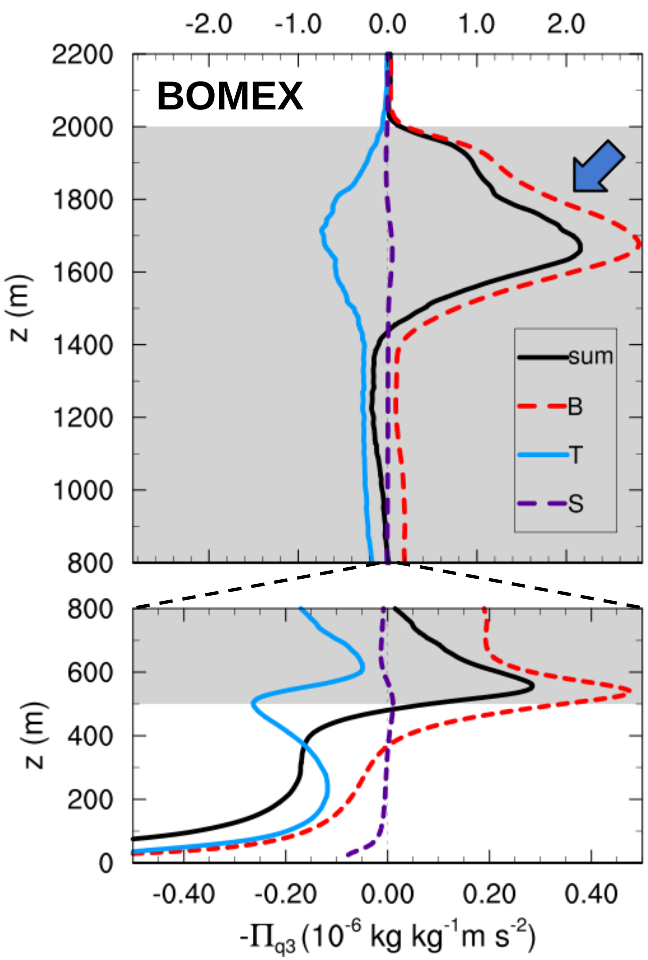
$$\Pi_{si} = \Pi_{si}^{\mathrm{T}} + \Pi_{si}^{\mathrm{S}} + \Pi_{si}^{\mathrm{B}} + \Pi_{si}^{\mathrm{C}}$$

- Solve Poisson equations for every component →

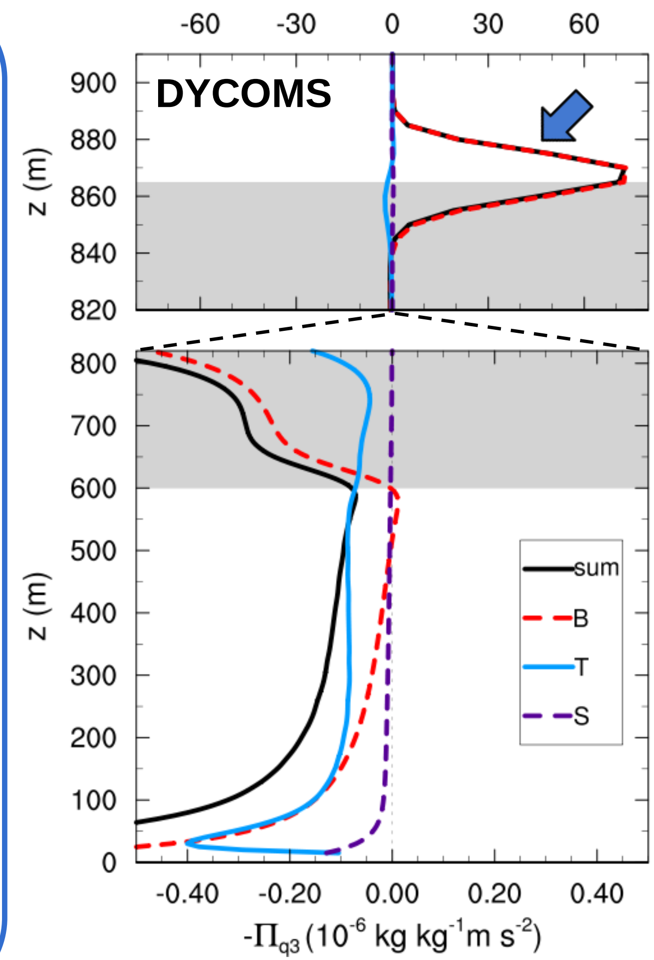
$$p' = p'_{\mathrm{T}} + p'_{\mathrm{S}} + p'_{\mathrm{B}} + p'_{\mathrm{C}}$$

- Analysis only possible with numerical data
- Implementation in PALM validated for free convection (Mironov 2001)

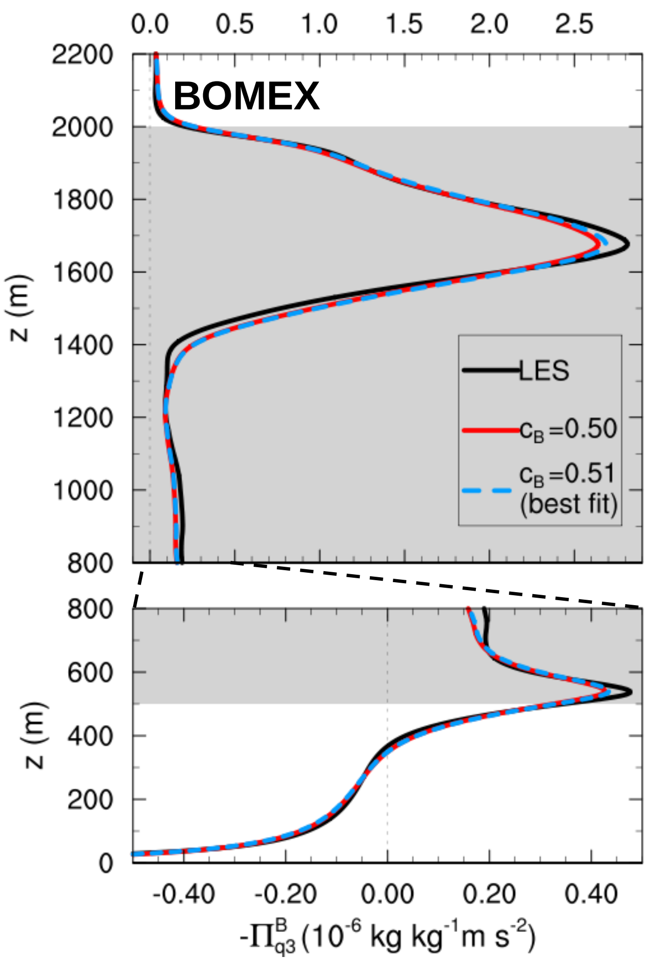
Contributions to Π_{q3} (q = total water specific humidity)



- Mixed layer and lower cloud layer: B and T are equally important
- Cloud top: correlation is dominated by B
- C contribution is negligible



Parameterization test (I) − Buoyancy ($s = q$)

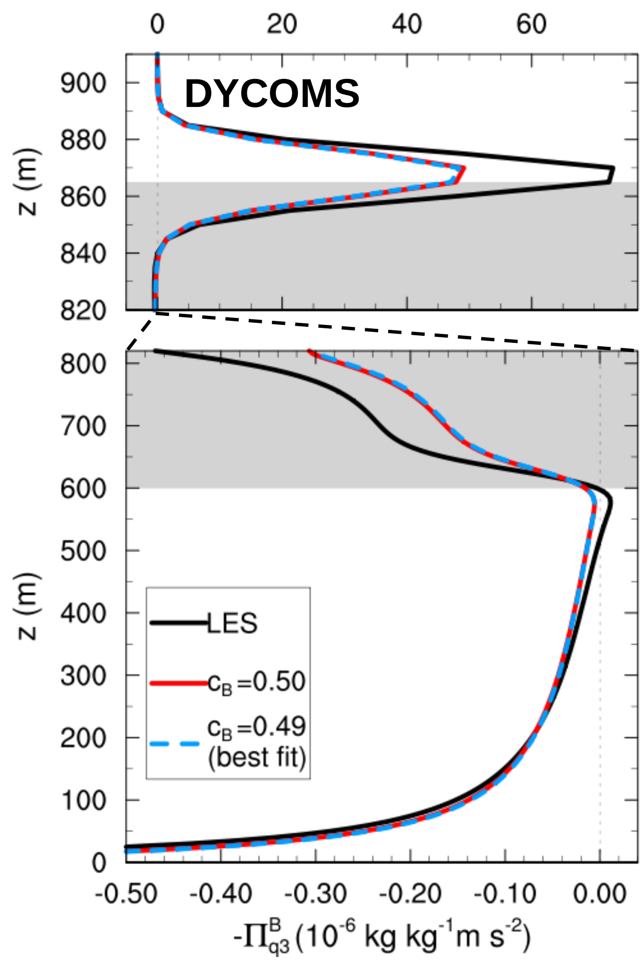


- Linear param.:

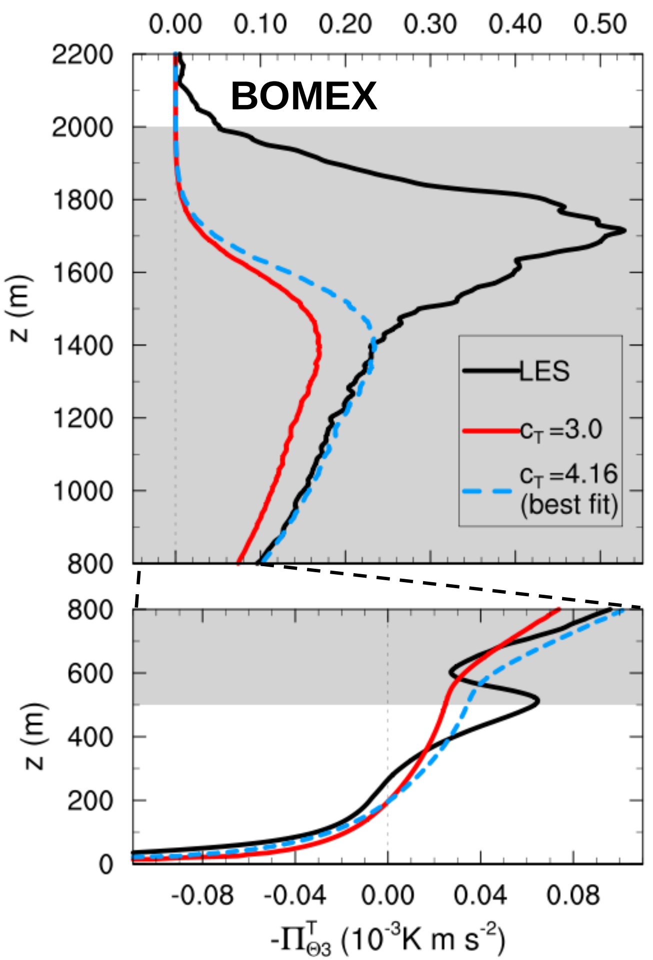
$$\Pi_{si}^{B} = c_{\mathrm{B}} \frac{g}{\theta_0} \delta_{i3} \overline{s'\theta_v'}$$

- Often used: $c_{\mathrm{B}} = 0.5$
- Underestimation at cloud top

$\Rightarrow$ Linear param. gives good agreement for both scalars $\rightarrow$ best fit: $c_{\mathrm{B}} \approx 0.5$



Parameterization test (II) – Turbulence ($s = \theta_\mathrm{l}$)



- Rotta param.:

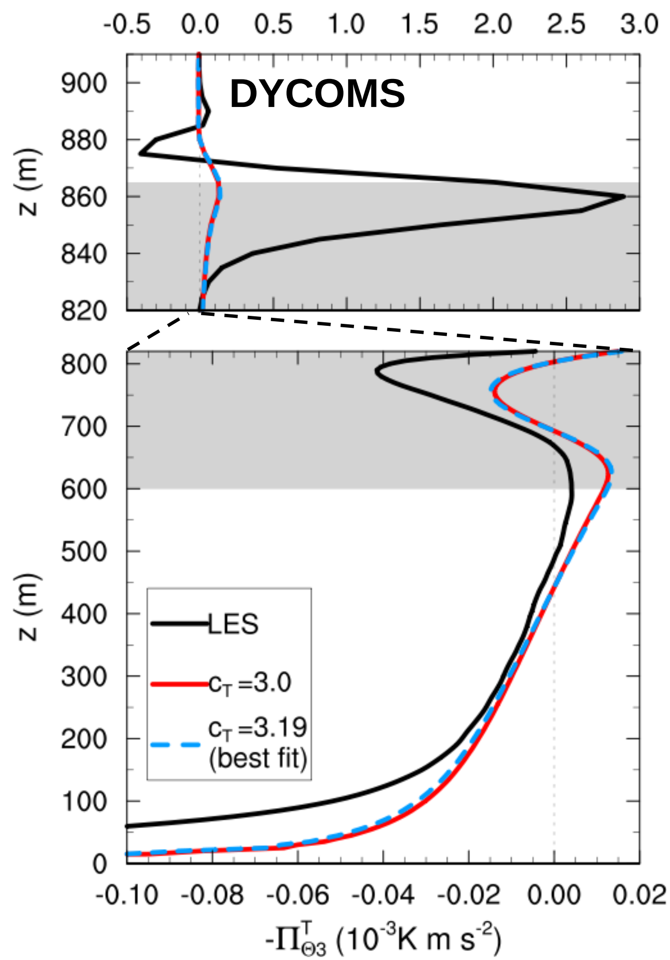
$$\Pi^T_{si} = c_\mathrm{T} \frac{\overline{u_i' s'}}{\tau}$$

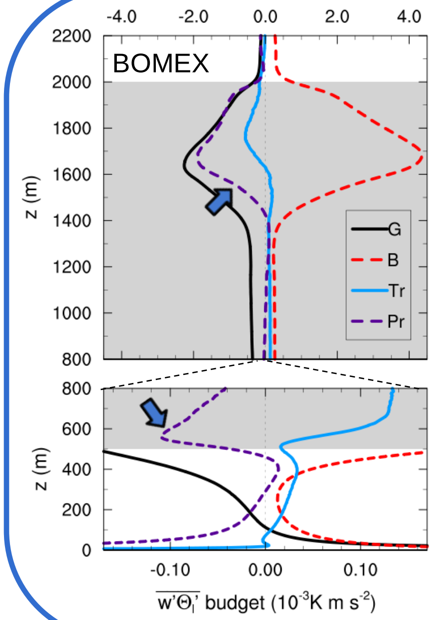
- Free convection:

$$c_\mathrm{T} \approx 3.0$$

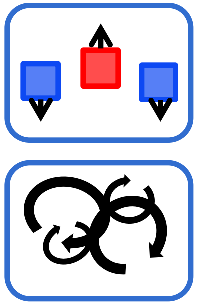
- Strong under-estimation at cloud top

$\Rightarrow$ Rotta param. agrees fairly well below cloud top $\rightarrow$ but no universal best-fit-value was found

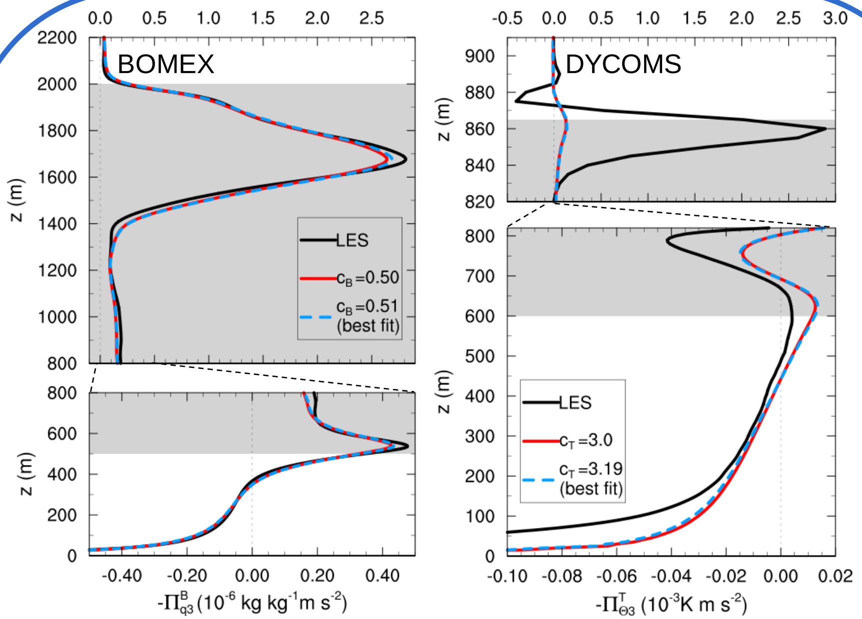




Scalar flux budget: pressure term Pr is important



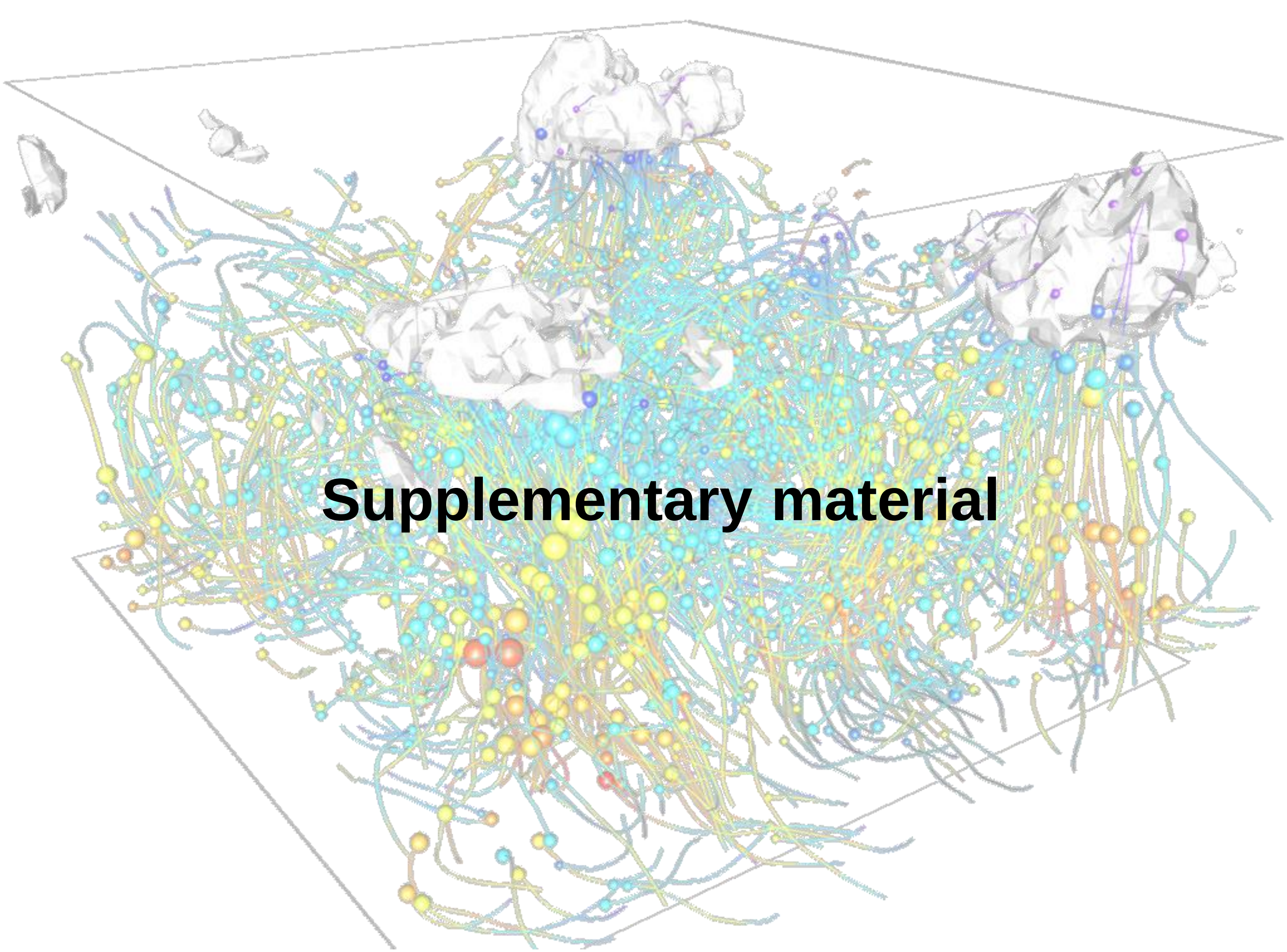
Decomposition: buoyancy (B) and turbulence (T) contribution are largest



Linear parameterizations:

- Work well for B → universal c_{B}
- Less satisfactory agreement for T → c_{T} depends on case and scalar

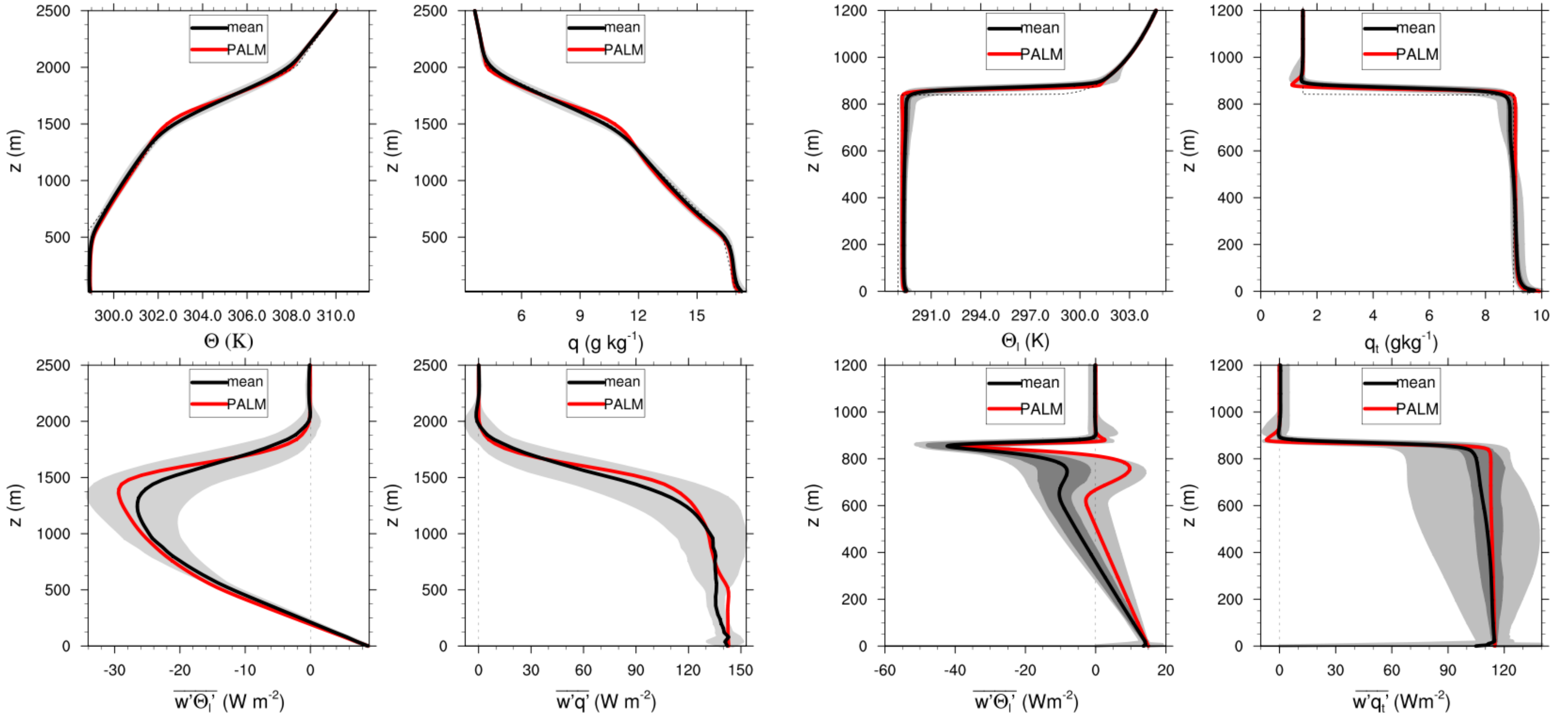
⇒ for higher accuracy: non-linear models necessary



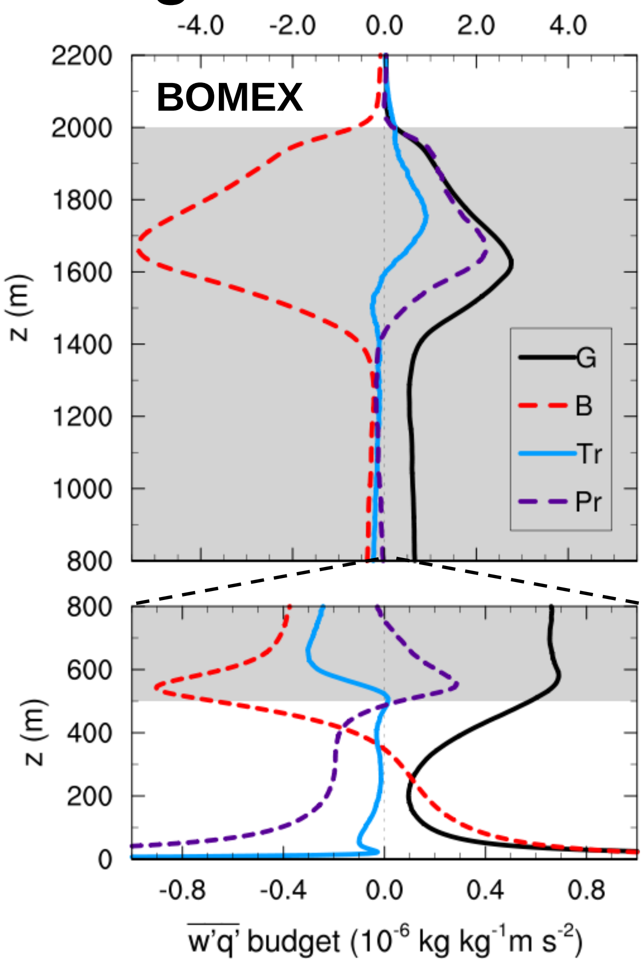
Supplementary material

Mean scalars and scalar fluxes

BOMEX DYCOMS



Budget of flux of total water content



$$\frac{\partial}{\partial t}\overline{w'q'} = \boxed{-\overline{w'^2}\frac{\partial \overline{q}}{\partial z}}$$

mean gradient

$$+\frac{g}{\theta_0}\overline{q'\theta'_{\mathrm{v}}}$$

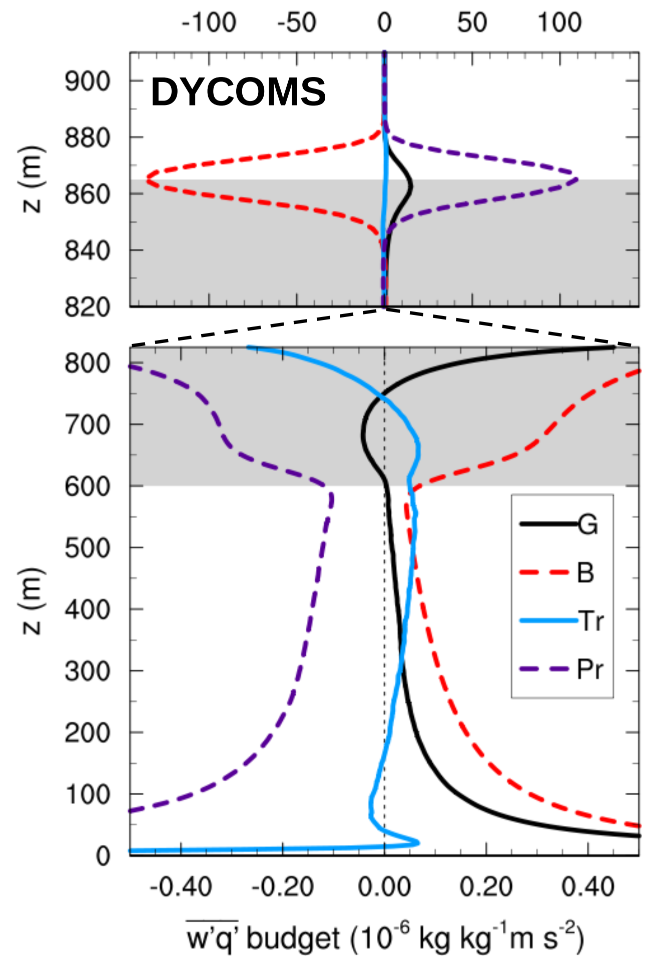
buoyancy

$$-\frac{\partial}{\partial z}\overline{w'^2 q'}$$

transport

$$-\frac{1}{\rho_0}\overline{q'\frac{\partial p'}{\partial z}}$$

pressure term



⇒ Dominated by mean-gradient (G), buoyancy (B) and pressure-term (Pr)

Decomposition

- Poisson equations for contribtutions of pressure fluctuations

$$p' = p'_\mathrm{T} + p'_\mathrm{S} + p'_\mathrm{B} + p'_\mathrm{C} + p'_\mathrm{SG}$$

- Due to LES: also subgrid contribution SG (very small)

- Boundary conditions:
  - Bottom: Neumann
  - Top: Dirichlet

$$\frac{1}{\rho_0}\frac{\partial^2 p'_\mathrm{T}}{\partial x_i^2} = -\frac{\partial^2}{\partial x_i \partial x_j}\left(u'_i u'_j - \overline{u'_i u'_j}\right)$$

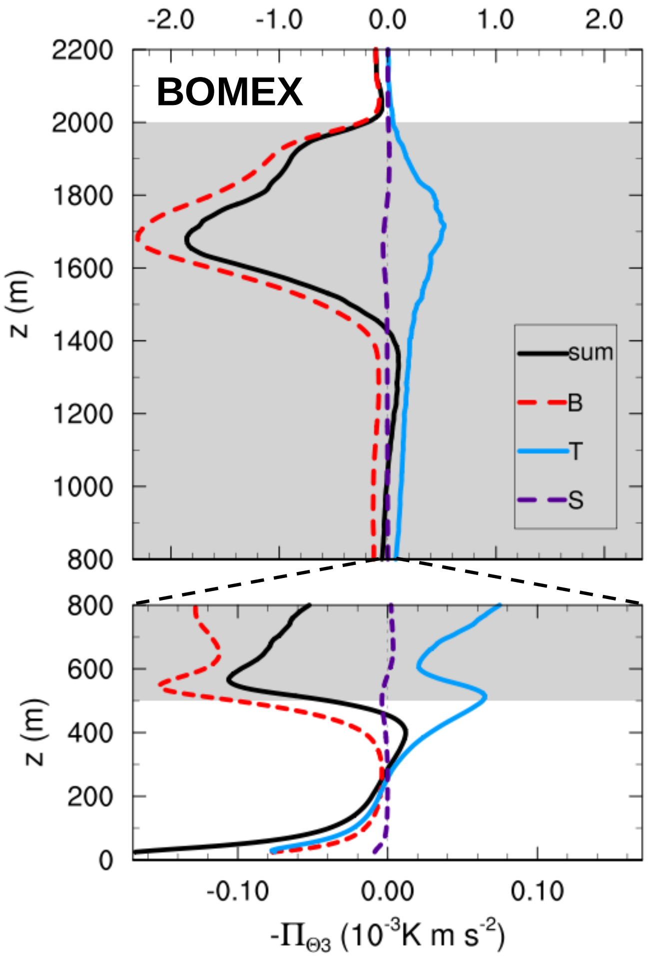
$$\frac{1}{\rho_0}\frac{\partial^2 p'_\mathrm{S}}{\partial x_i^2} = -2\frac{\partial u'_j}{\partial x_i}\frac{\partial \overline{u}_i}{\partial x_j}$$

$$\frac{1}{\rho_0}\frac{\partial^2 p'_\mathrm{B}}{\partial x_i^2} = \frac{g}{\theta_0}\frac{\partial \theta'_v}{\partial x_3}$$

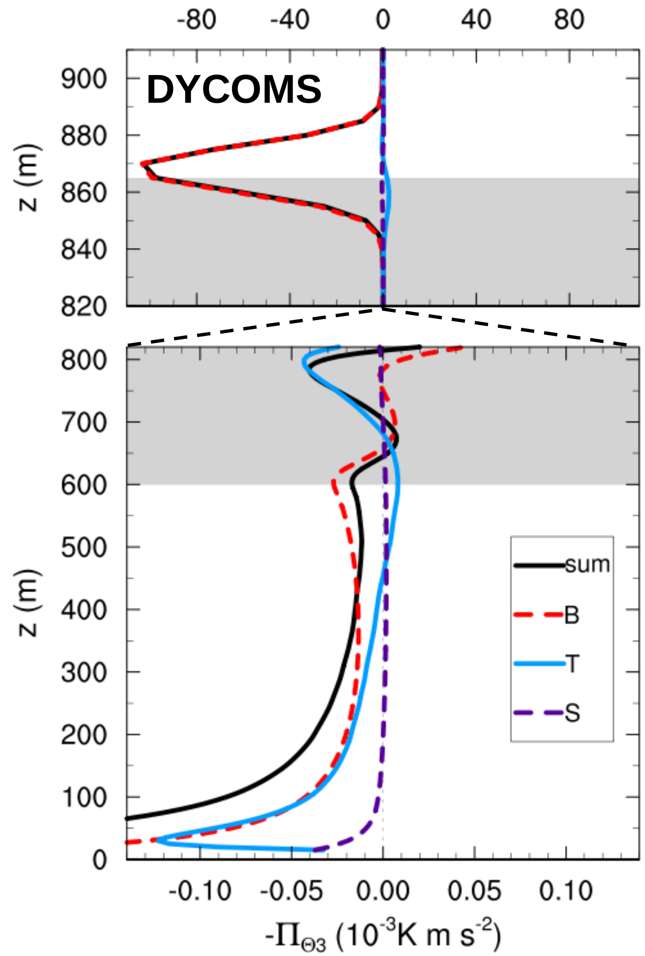
$$\frac{1}{\rho_0}\frac{\partial^2 p'_\mathrm{C}}{\partial x_i^2} = -\varepsilon_{ijk} f_j \frac{\partial u'_k}{\partial x_i}$$

$$\frac{1}{\rho_0}\frac{\partial^2 p'_\mathrm{SG}}{\partial x_i^2} = -\frac{\partial^2 \tau'_{ij}}{\partial x_i \partial x_j}$$

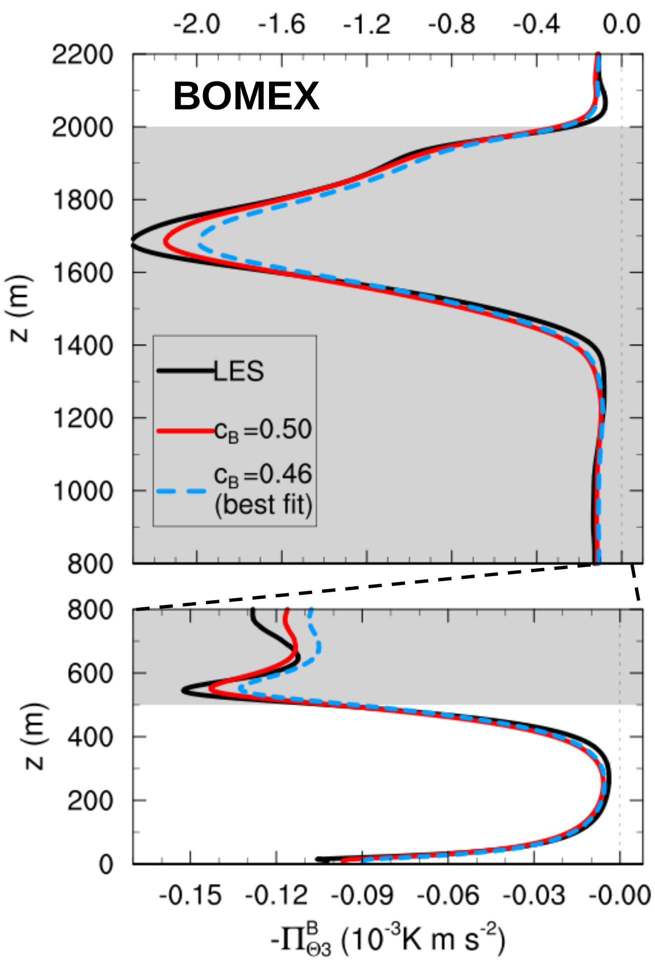
Contributions of $\Pi_{\theta 3}$



- Similar to decomposition of Π_{q3} (→ slide 6)
- B is most important contribution



Parameterization test – Buoyancy ($s = \theta_\mathrm{l}$)



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- Often used:
  $c_\mathrm{B} = 0.5$
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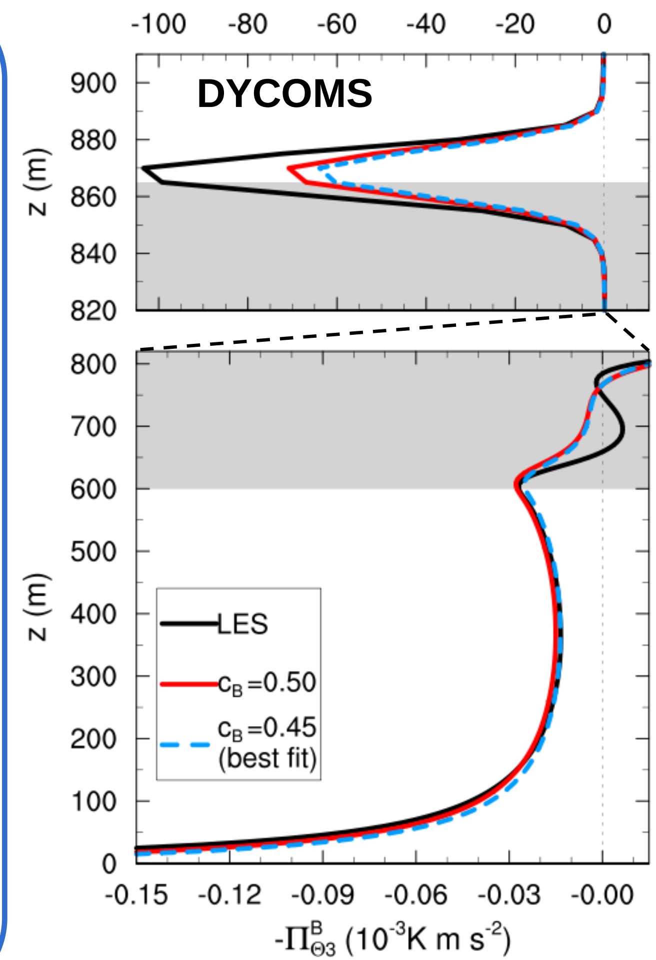
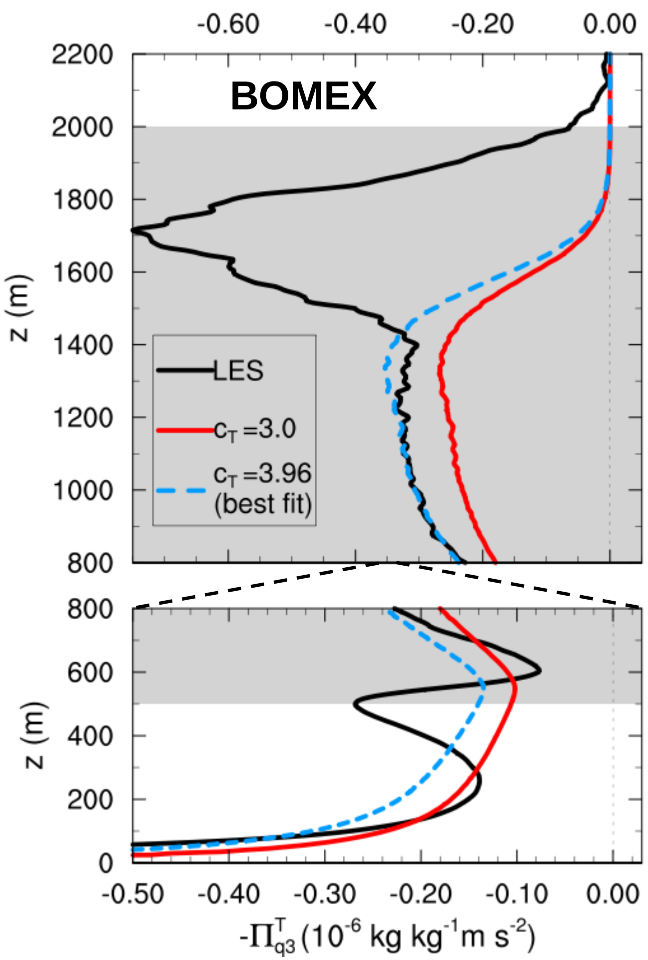
$c_\mathrm{B} \approx 0.5$



Parameterization test – Turbulence ($s = q$)



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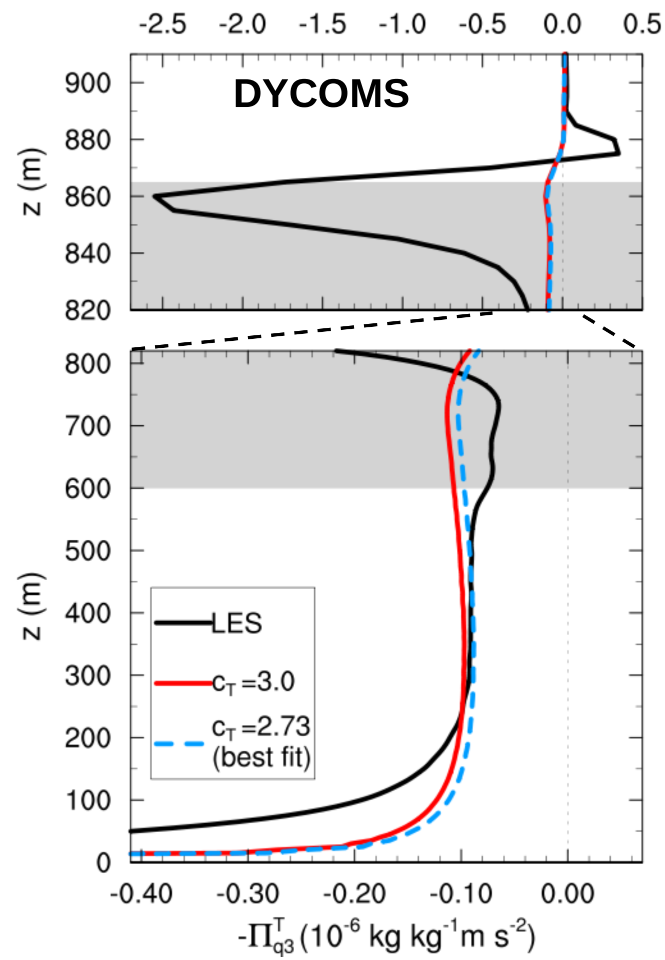

Return-to-isotropy time scale

- Return-to-isotropy time scale is usally modeled as $\tau = \overline{e}/\overline{\varepsilon}$
- Instead: usage of other time scales: $\tau_\theta = \overline{\theta_l}/\overline{\varepsilon}_\theta$ or $\tau_q = \overline{q}/\overline{\varepsilon}_q$