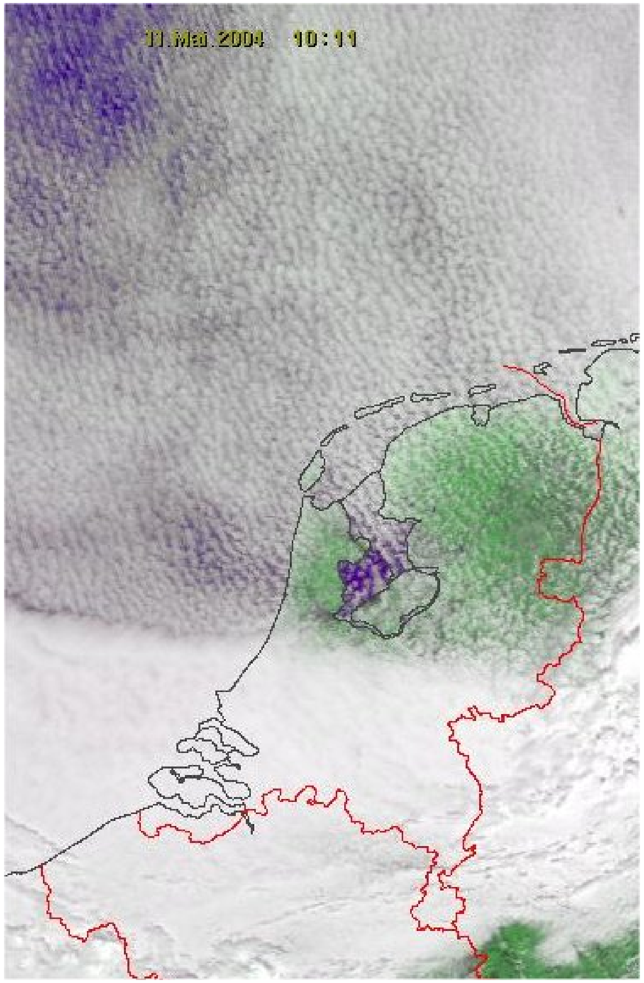
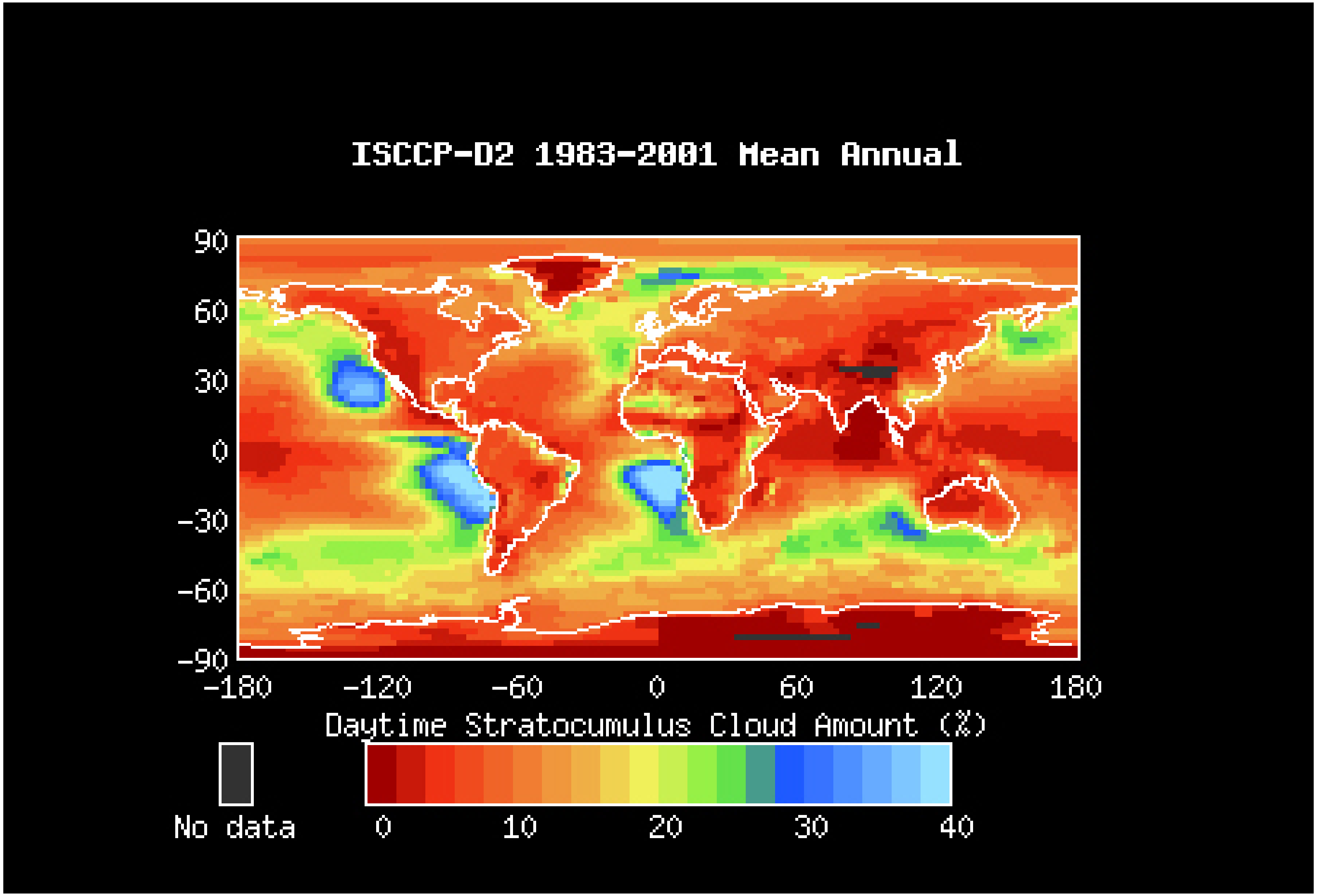
The representation of stratocumulus with eddy diffusivity closure models



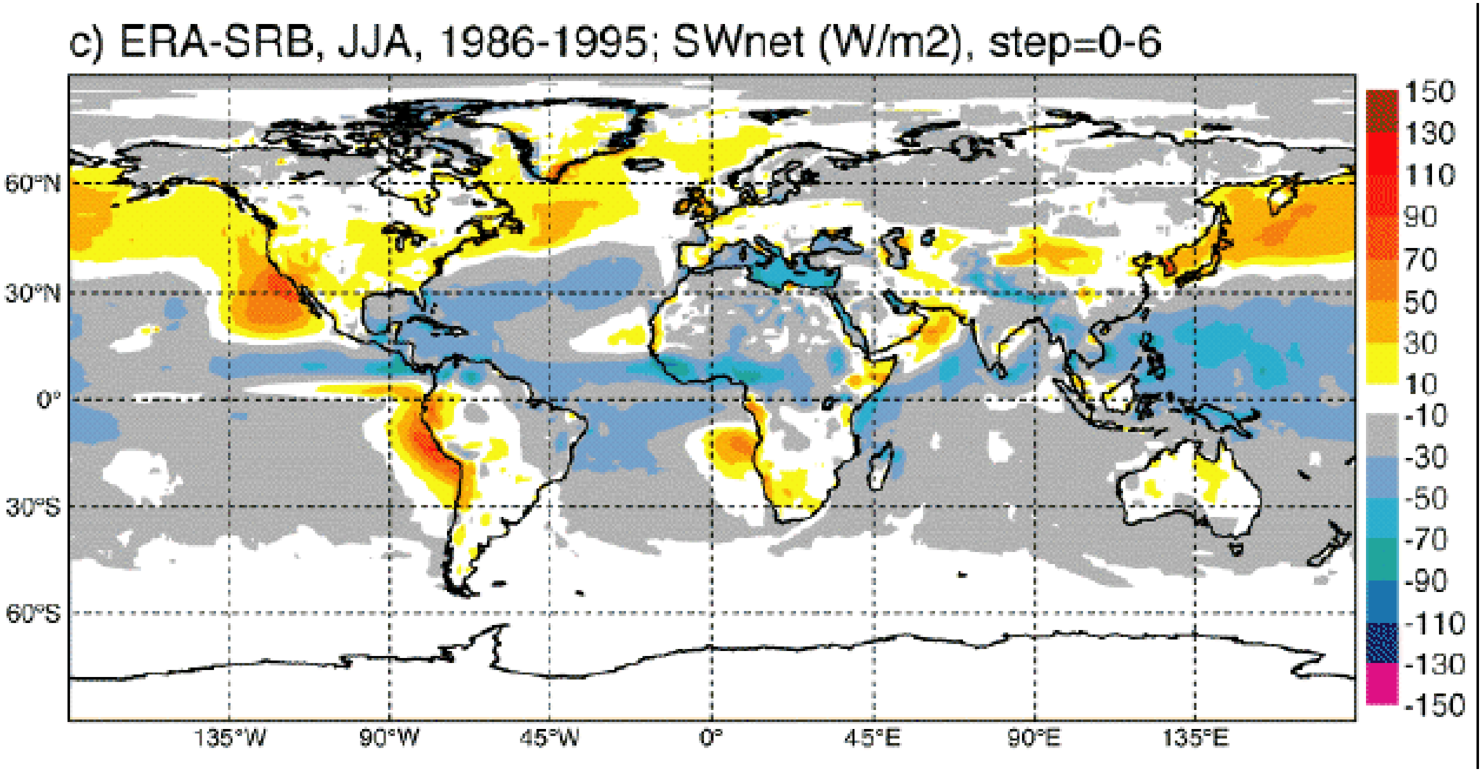
Stephan de Roode

KNMI

Global stratocumulus presence



Motivation of the problem



ECMWF underestimates stratocumulus

ECMWF underpredicts stratocumulus Liquid Water Path (LWP)

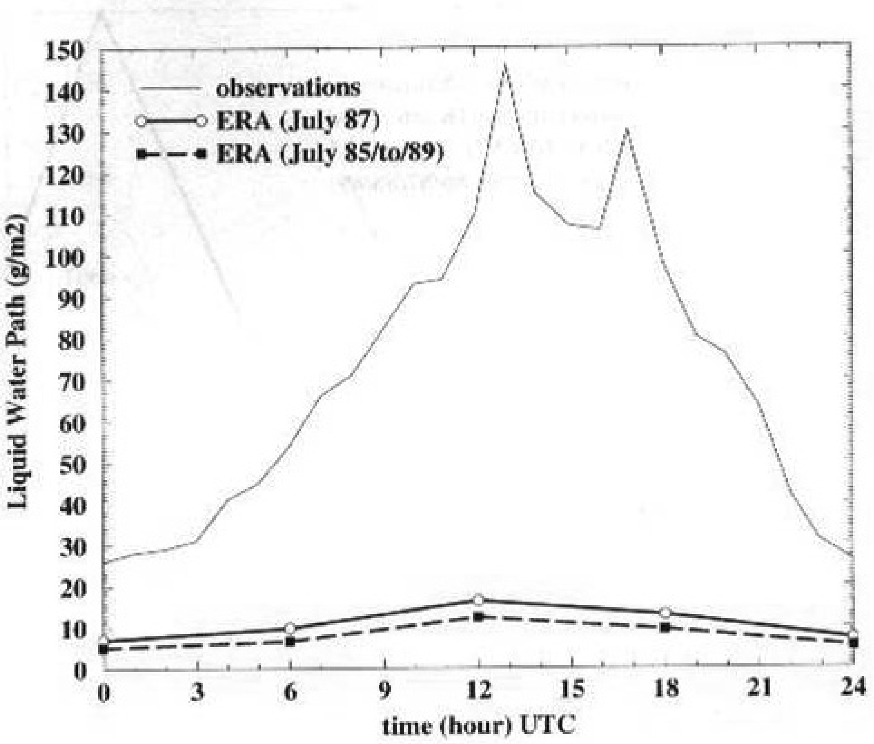


FIG. 6. Mean diurnal variation of liquid water path: FIRE I observations from 1 to 19 Jul 1987 (thin line), Jul 1987 of ERA (thick full line), and Jul 1985–89 of ERA (dashed line).

Duynkerke and Teixeira (2001)

RACMO uses ECMWF physics!

Entrainment of relatively warm and dry inversion air into the cloudy boundary layer

Bjorn Stevens

Entrainment: the holy grail in stratocumulus research

"Dogma": solve the stratocumulus problem by **getting the entrainment rate right** in a model

Topics:

1. Dogma is not true
2. Entrainment rates from a TKE scheme compared to parameterizations

Turbulent transport in closure models

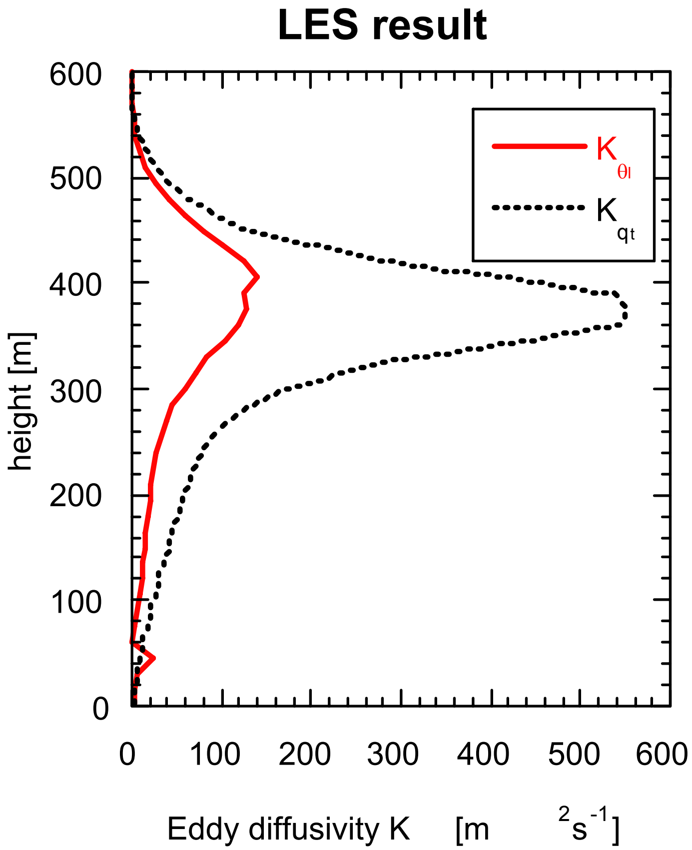
Tendency equation for the mean

$$\frac{\partial \overline{\psi}}{\partial t} = -\frac{\partial \overline{w'\psi'}}{\partial z} + S_\psi$$

Computation of the flux

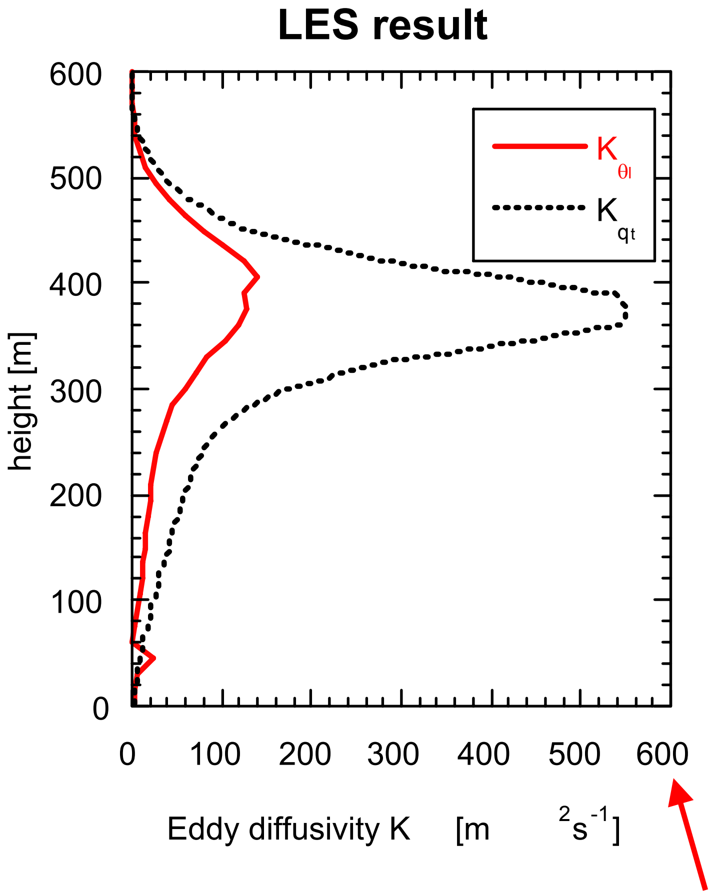
$$\overline{w'\psi'} = -\boxed{K_\psi}\frac{\partial \overline{\psi}}{\partial z}$$

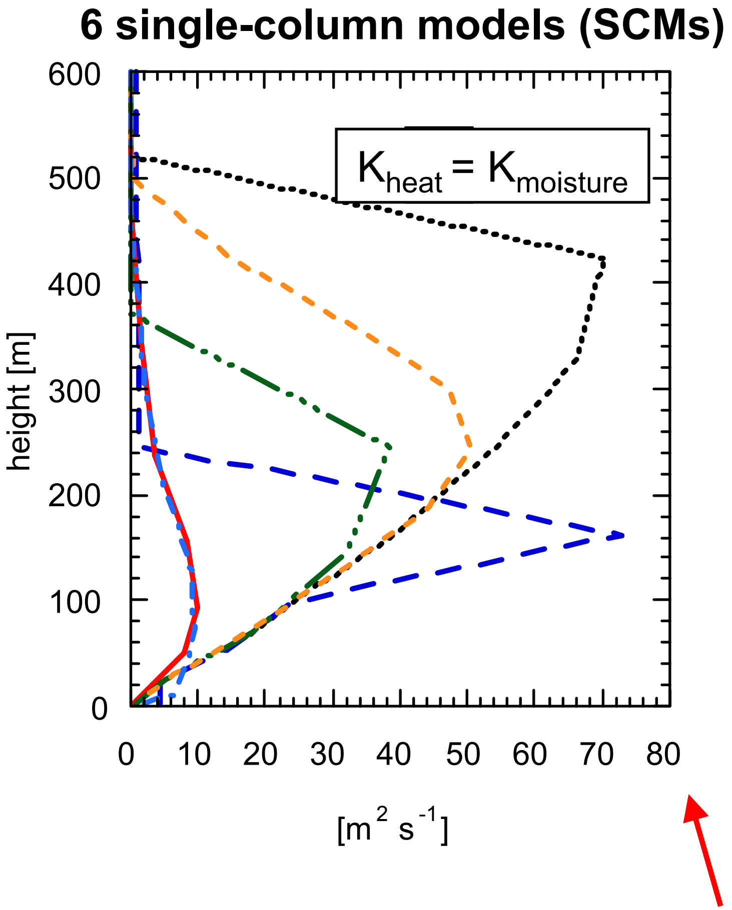
Eddy diffusivities diagnosed from LES results - Results from the FIRE I stratocumulus intercomparison case



- **LES: Eddy diffusivities for heat and moisture differ**

Eddy diffusivities in K-closure models -
Results from the FIRE I stratocumulus intercomparison case





- **LES: Eddy diffusivities for heat and moisture differ**

- **SCM: typically much smaller values than LES**

Should we care about eddy diffusivity profiles in SCMs?

Simple experiment

1. Prescribe surface latent and sensible heat flux

2. Prescribe entrainment fluxes

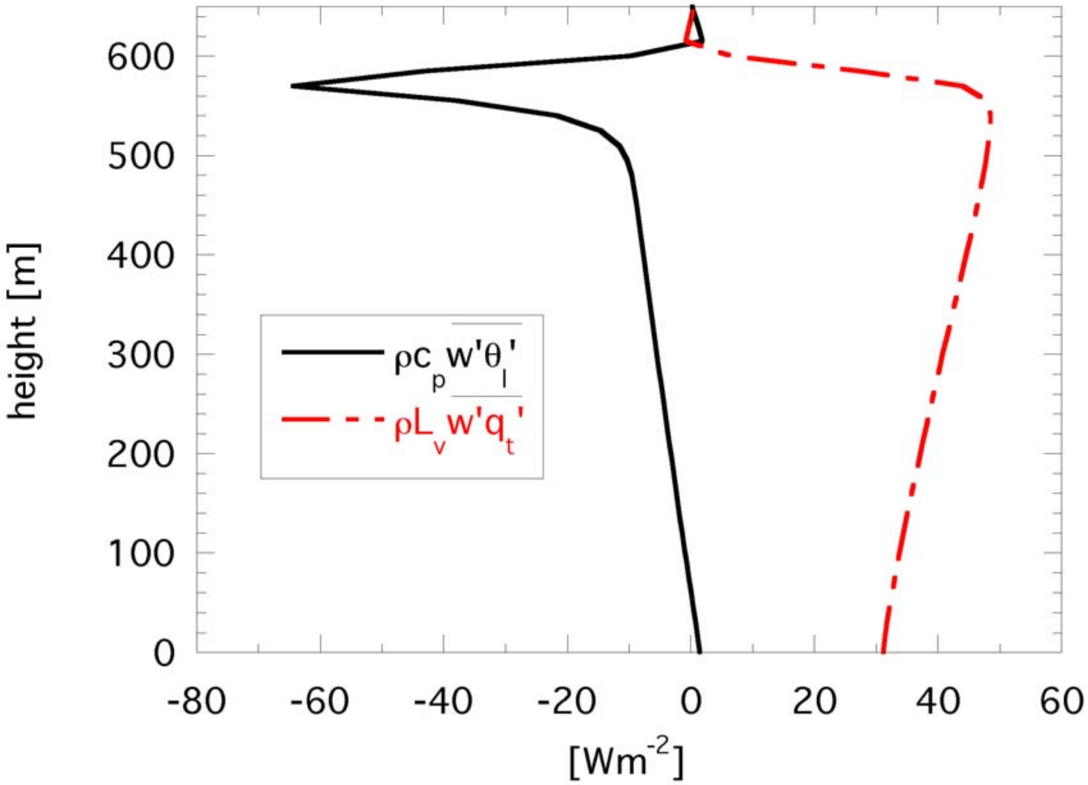
3. Consider quasi-steady state solutions

$\Rightarrow$ fluxes linear function of height

Consider mean state solutions from

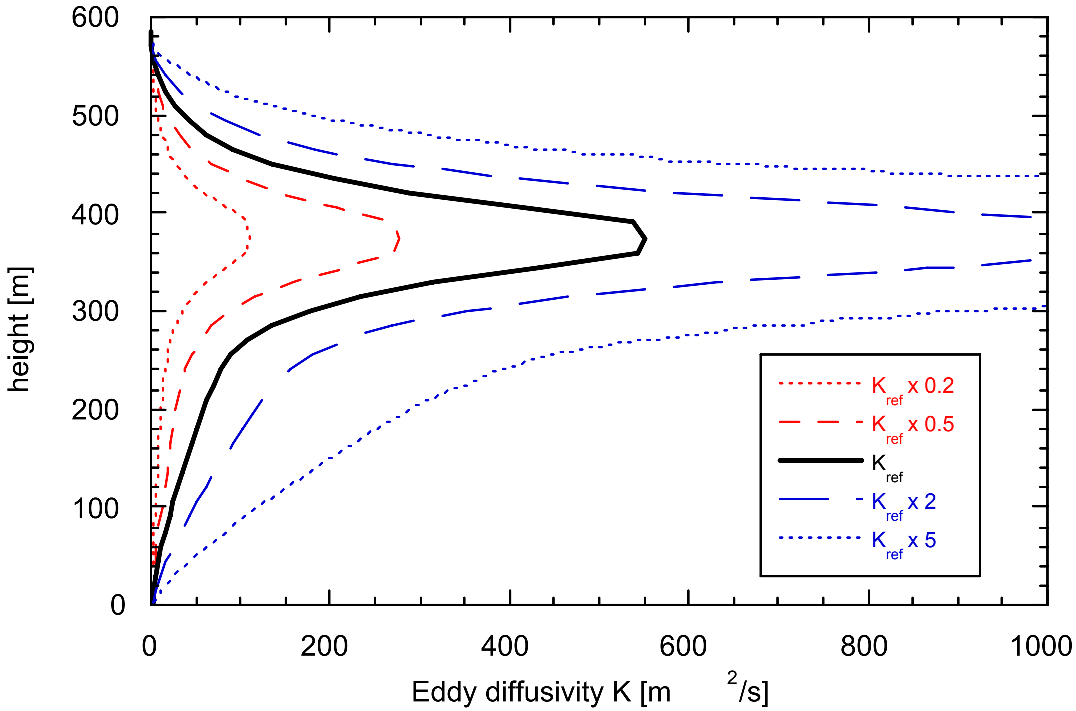
$$\overline{\psi}(z) = \psi_0 - \int_{z'=0}^{z'=z} \frac{\overline{w'\psi'}(z')}{K_\psi(z')} dz'$$

Use fixed flux profiles from LES results (so we know the entrainment fluxes)



$$\overline{\psi}(z) = \psi_0 - \int_{z'=0}^{z'=z} \frac{\boxed{\overline{w'\psi'}(z')}}{K_\psi(z')} dz'$$

Vary eddy diffusivity profiles with a constant factor c



- **K_{ref} is identical to K_{qt} from LES**
- **Multiply K_{ref} times constant factor c**

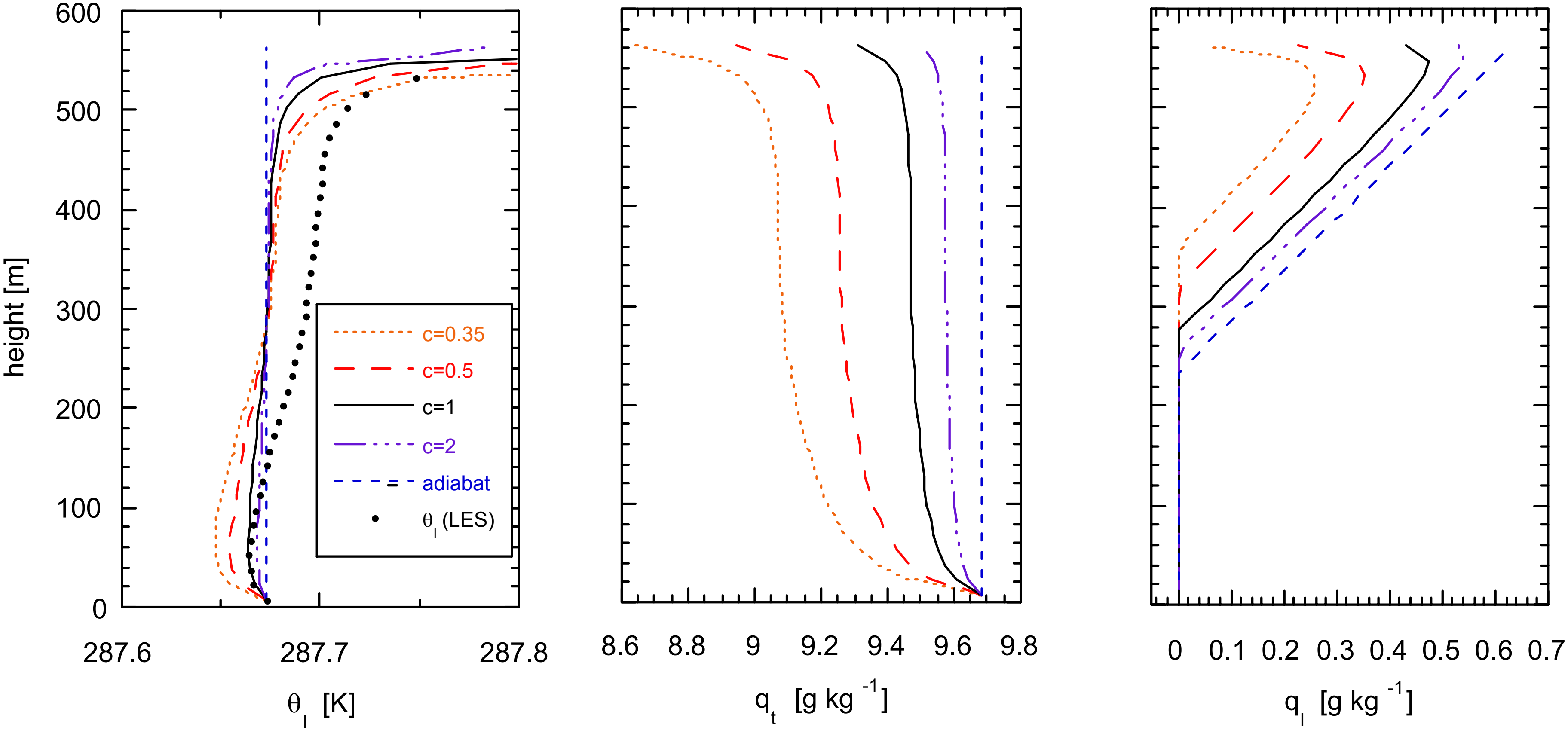
$$\overline{\psi}(z) = \psi_0 - \int_{z'=0}^{z'=z} \frac{\overline{w'\psi'}(z')}{\boxed{K_\psi(z')}} dz'$$

Remember the dogma?

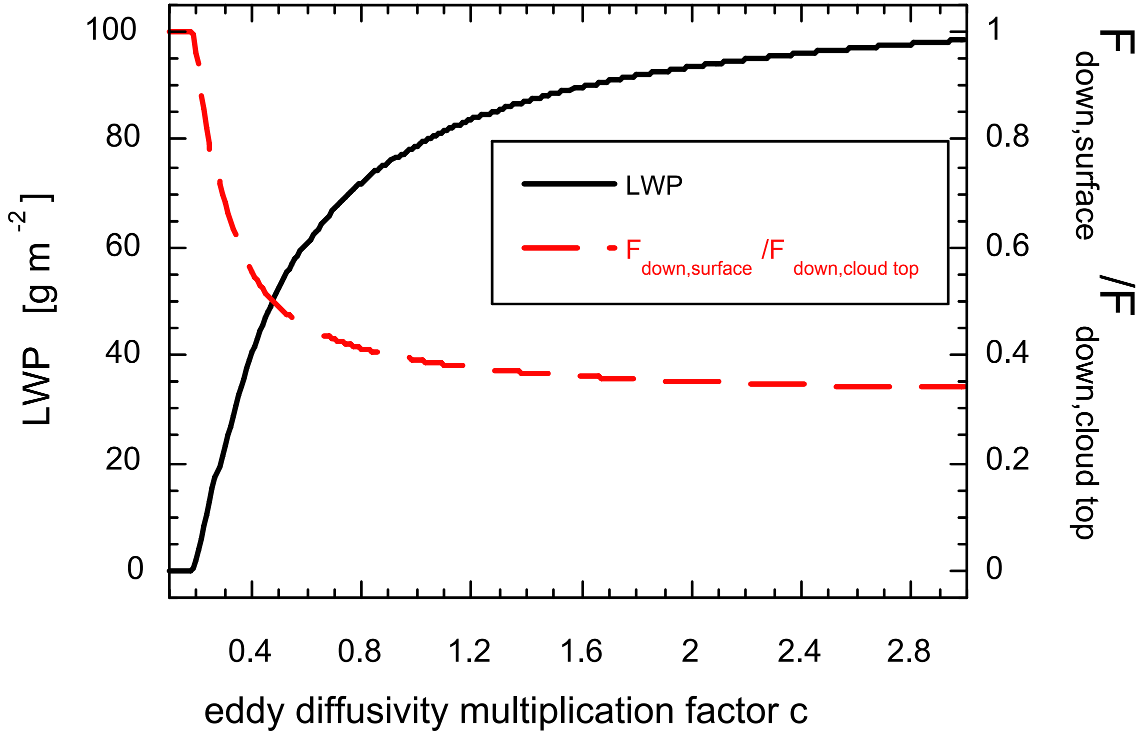
Dogma: solve the stratocumulus problem by **getting the entrainment rate right** in a model

If we prescribe the entrainment fluxes, **do we get the right cloud structure?**

Mean state solutions

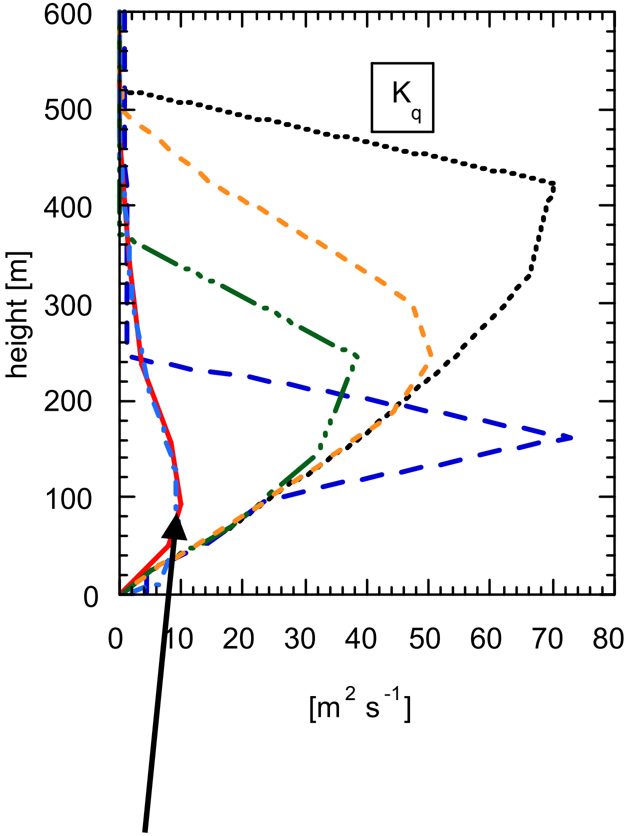


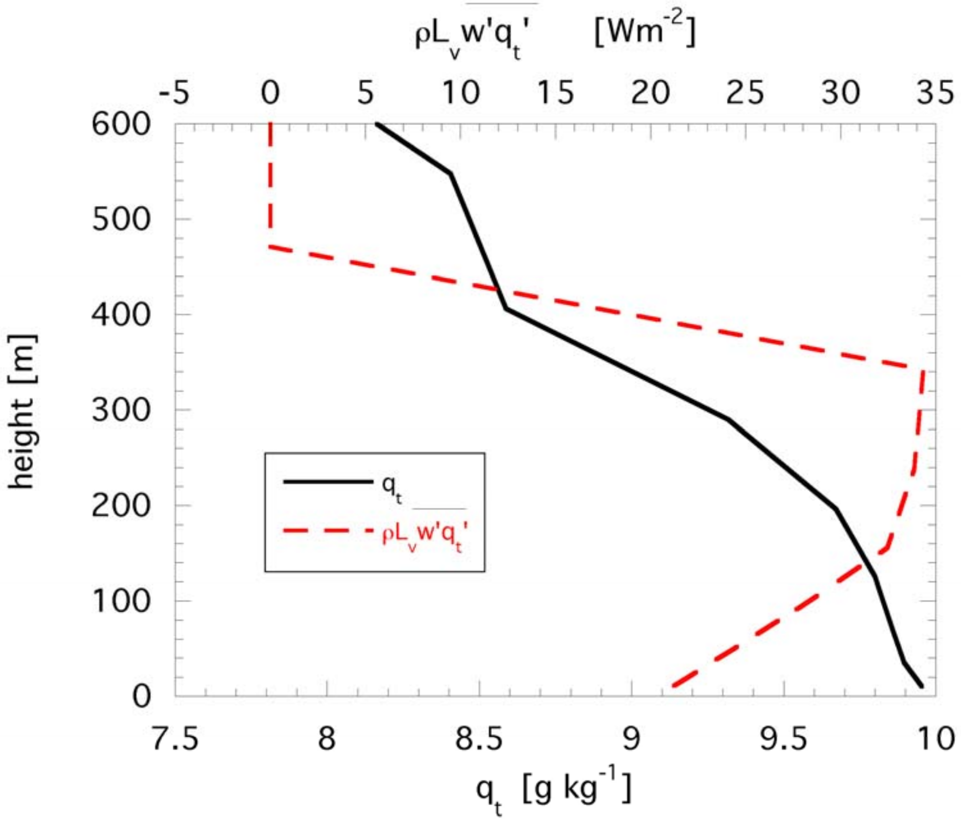
Liquid Water Path and cloud transmissivity



LWP and cloud transmission VERY sensitive to eddy-diffusivity profile

ECMWF low eddy diffusivities explain low specific humidity





ECMWF eddy diffusivity from Troen and Mahrt (1986)

$$K_h = \left(u_*^{\,3} + c w_*^{\,3}\right) h k \frac{z}{h}\left(1-\frac{z}{h}\right)^p$$

$$w_*^{\,3} = \frac{gh}{T_0}\overline{w'\theta_v'}_0$$

Turbulent mixing and entrainment in simple closure models

Computation of the flux $\overline{w'\psi'} = -K_\psi \frac{\partial \overline{\psi}}{\partial z}$

Representation of entrainment rate w_e

ECMWF K-profile $K = w_e \Delta z$, w_e from parametrization

RACMO TKE model $K(z) = TKE(z)^{1/2}\, l(z)$, w_e implicit

Question

Does w_e from a TKE model compare well to w_e from parametrizations?

Entrainment parameterizations designed from LES of stratocumulus (*Stevens 2002*)

- Nicholls and Turton (1986)

$$w_e = \frac{2.5 A W_{NE}}{\Delta\theta_{v,NT} + 2.5 A \left(T_2 \Delta\theta_{v,dry} + T_4 \Delta\theta_{v,sat} \right)}$$

- Lilly (2002)

$$w_e = \frac{A_{DL} W_{NE,DL}}{\Delta\theta_{v,DL} + A_{DL} \left(L_2 \Delta\theta_{v,dry} + L_4 \Delta\theta_{v,sat} \right)}$$

- Stage and Businger (1981)
  Lewellen and Lewellen (1998)
  VanZanten et al. (1999)

$$w_e = \frac{A W_{NE}}{T_2 \Delta\theta_{v,dry} + T_4 \Delta\theta_{v,sat}}$$

- Lock (1998)

$$w_e = \frac{2 A_{AL} W_{NE} + \alpha_t A_W \Delta F_L / \left(\rho c_p \right)}{\Delta\theta_v}$$

- Moeng (2000)

$$w_e = \frac{A_M \overline{w'\theta_l'} + \Delta F_L \left(3 - e^{-\sqrt{b_m L}} \right) / \left(\rho c_p \right)}{\Delta\theta_l}$$

w_e = fct (H, LE, z_b, z_i, $\Delta F_{l,}$ Δq_t, $\Delta\theta_l$, LWP or $q_{l,max}$)

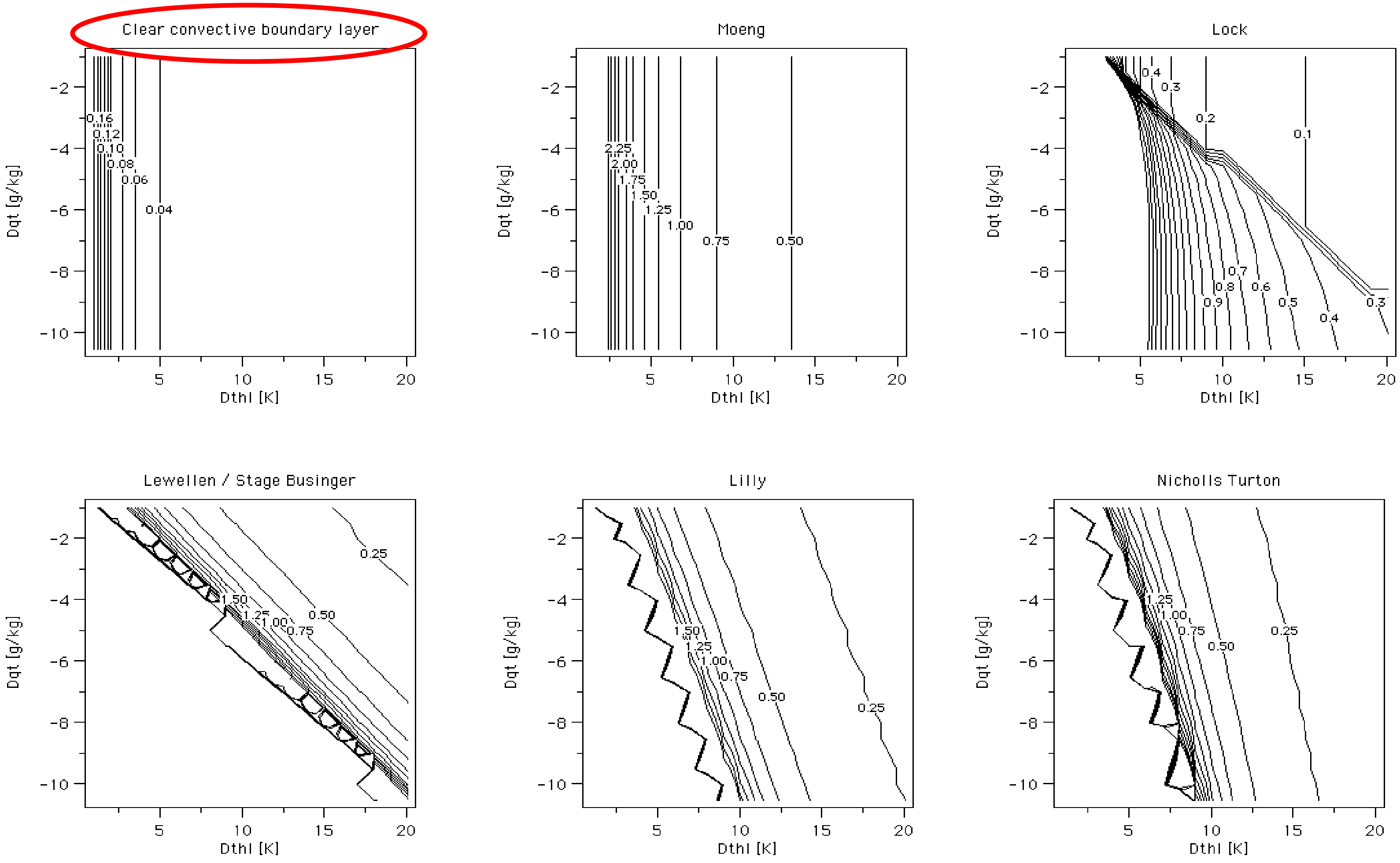
Simulation of ASTEX stratocumulus case

ASTEX A209 boundary conditions

cloud base height = 240 m
cloud top height = 755 m
sensible heat flux = 10 W/m^2
latent heat flux = 30 W/m^2
longwave flux jump = 70 W/m^2
max liq. water content = 0.5 g/kg
LWP = 100 g/m^2
$\Delta\theta_l$ = 5.5 K
Δq_t = -1.1 g/kg

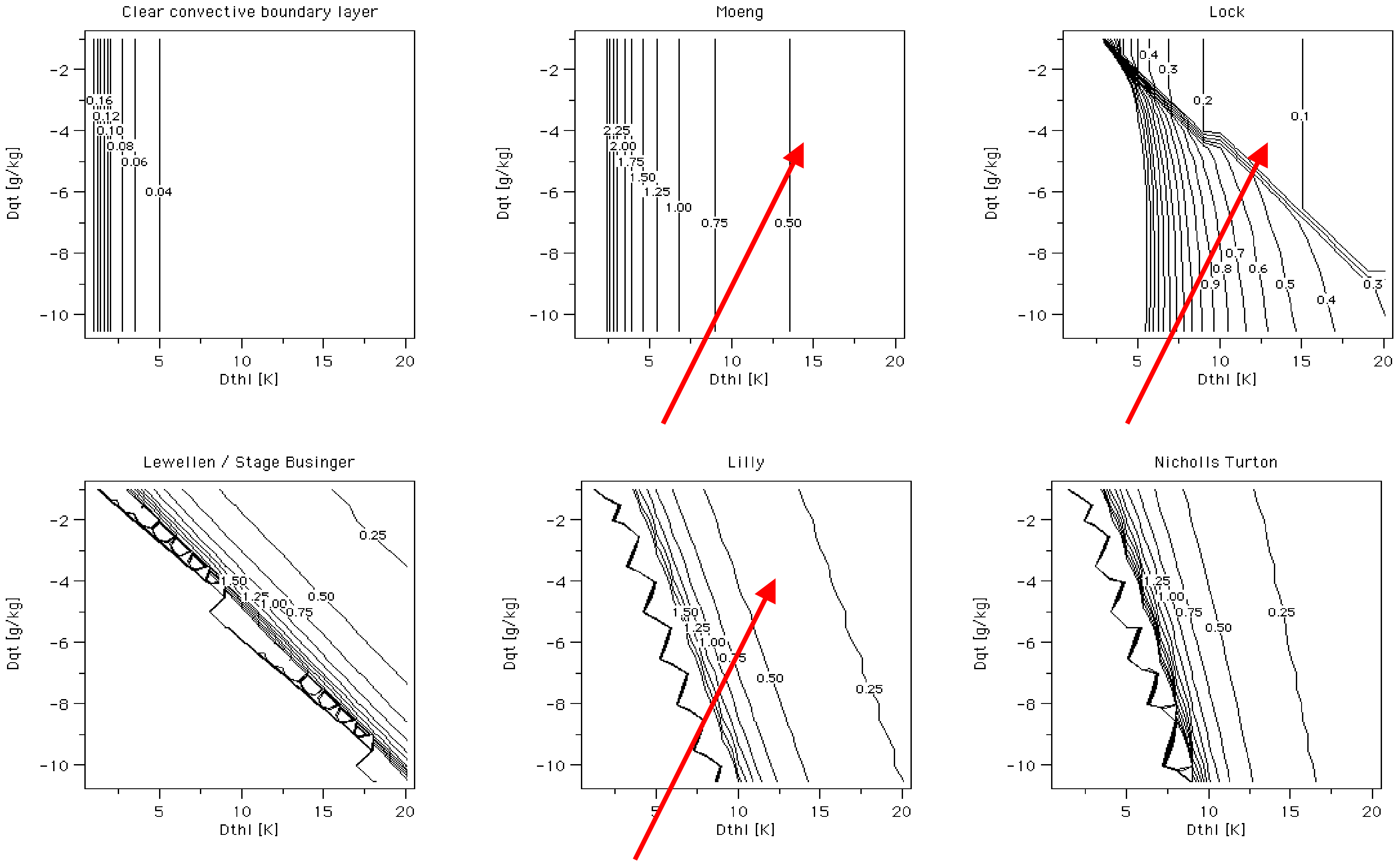
fill in these values in parameterizations,
but vary the inversion jumps $\Delta\theta_l$ and Δq_t

Entrainment rate [cm/s] sensitivity to inversion jumps - Boundary conditions as for ASTEX A209



1. **Note differences**
2. **Buoyancy reversal**
3. **Moisture jump sensitivity**

Entrainment rate [cm/s] sensitivity to inversion jumps - Boundary conditions as for ASTEX A209



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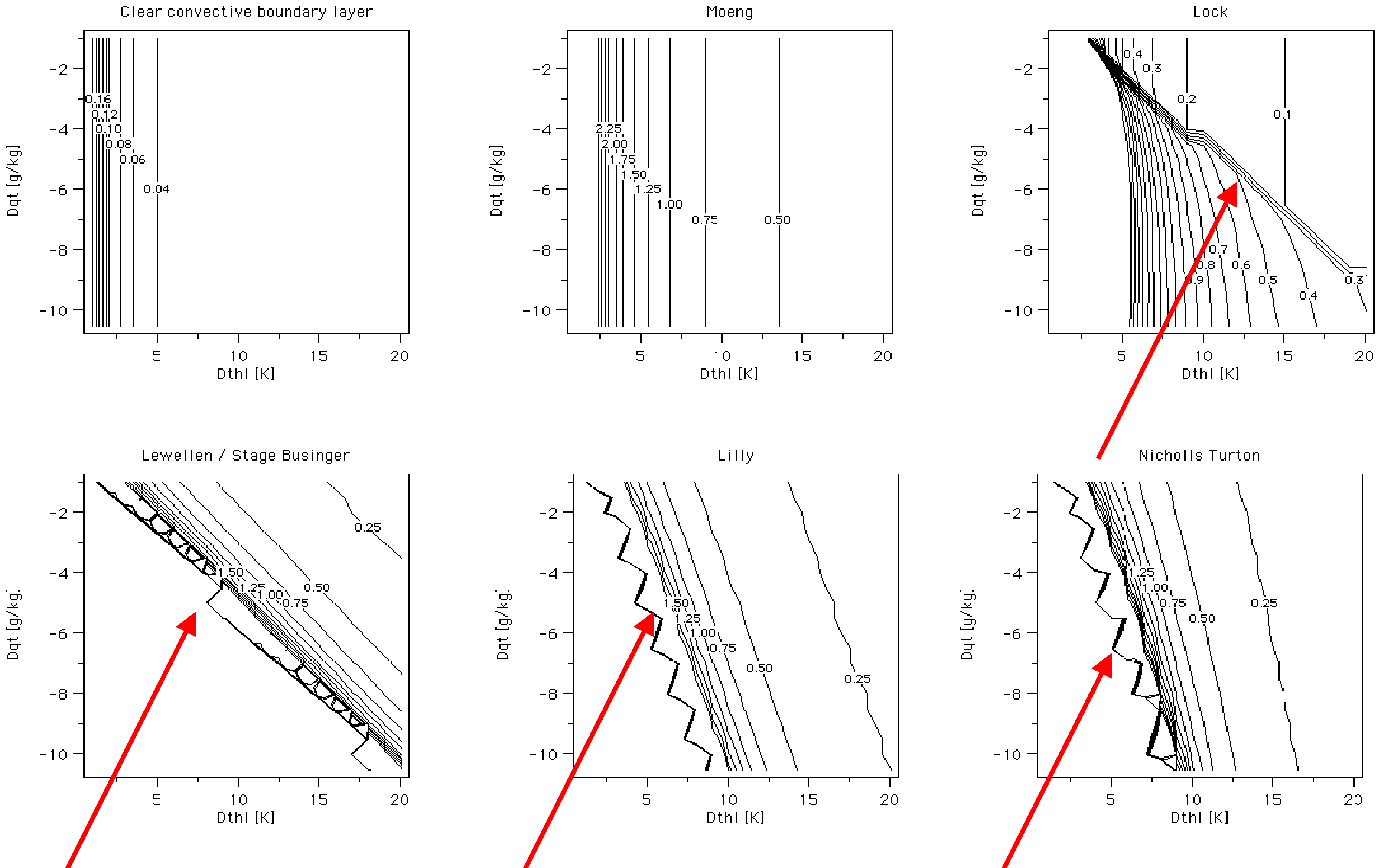

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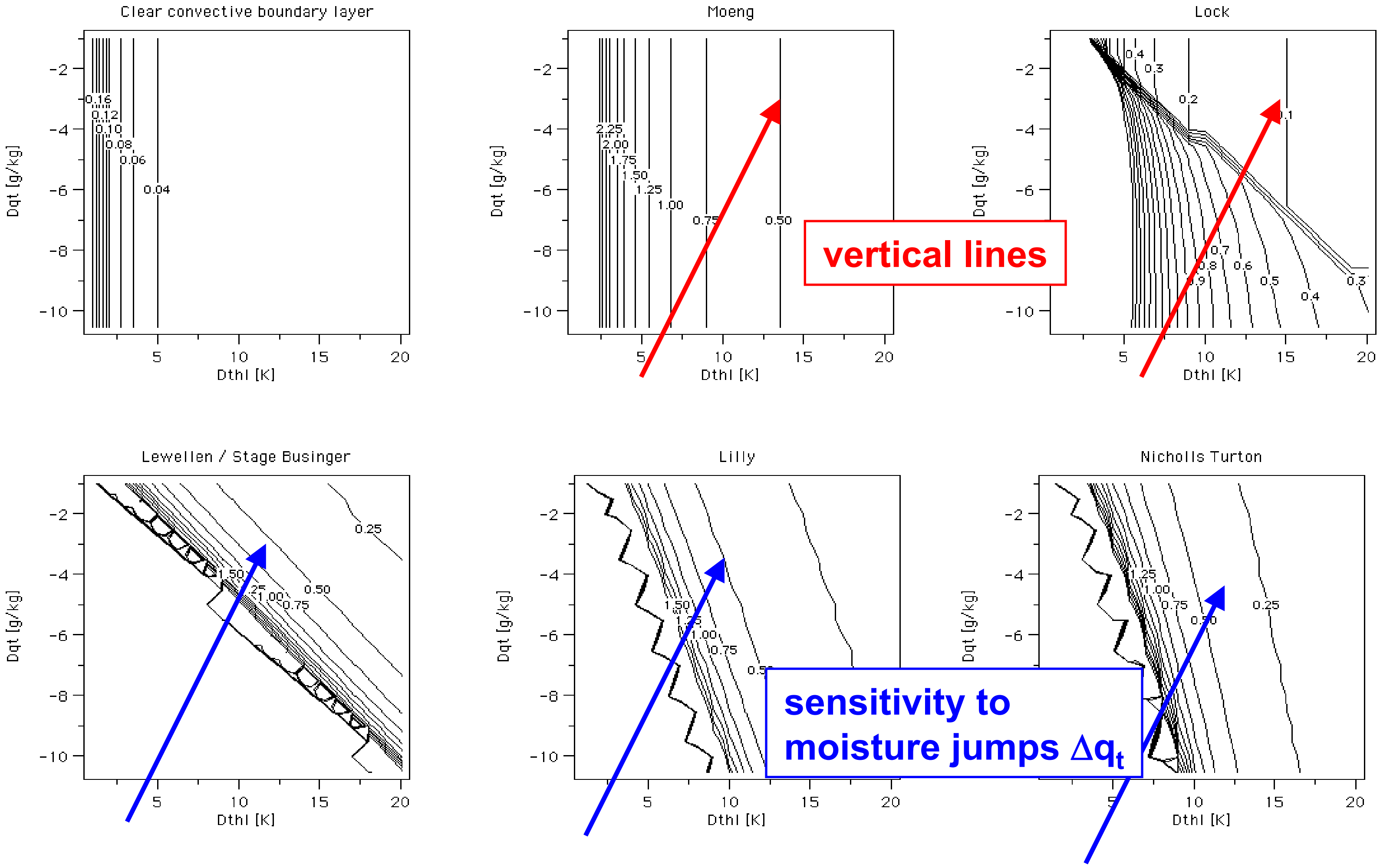
Entrainment rate [cm/s] sensitivity to inversion jumps - Boundary conditions as for ASTEX A209



vertical lines

sensitivity to moisture jumps Δq_t

1. **Note differences**
2. **Buoyancy reversal**
3. **Moisture jump sensitivity**

RACMO

How does a TKE model represent entrainment?

- Some model details

- Run ASTEX stratocumulus, and check sensitivity to entrainment jumps

Some details of the TKE model simulation

- TKE equation

$$\frac{\partial \overline{E}}{\partial t} = \frac{g}{\overline{\theta_v}}\overline{w'\theta_v'} - \overline{u'w'}\frac{\partial U}{\partial z} - \overline{v'w'}\frac{\partial V}{\partial z} - \frac{\partial}{\partial z}\left(\overline{w'E'} + \frac{\overline{w'p'}}{\rho}\right) - \varepsilon$$

- Flux

$$\overline{w'\psi'} = -c_\psi \sqrt{TKE}\,\ell \frac{\partial \overline{\psi}}{\partial z}$$

- 'integral' length scale

$$\frac{1}{\ell} = \frac{1}{\ell_u} + \frac{1}{\ell_d}$$

(Lenderink & Holtslag 2004)

- buoyancy flux weighed with cloud fraction

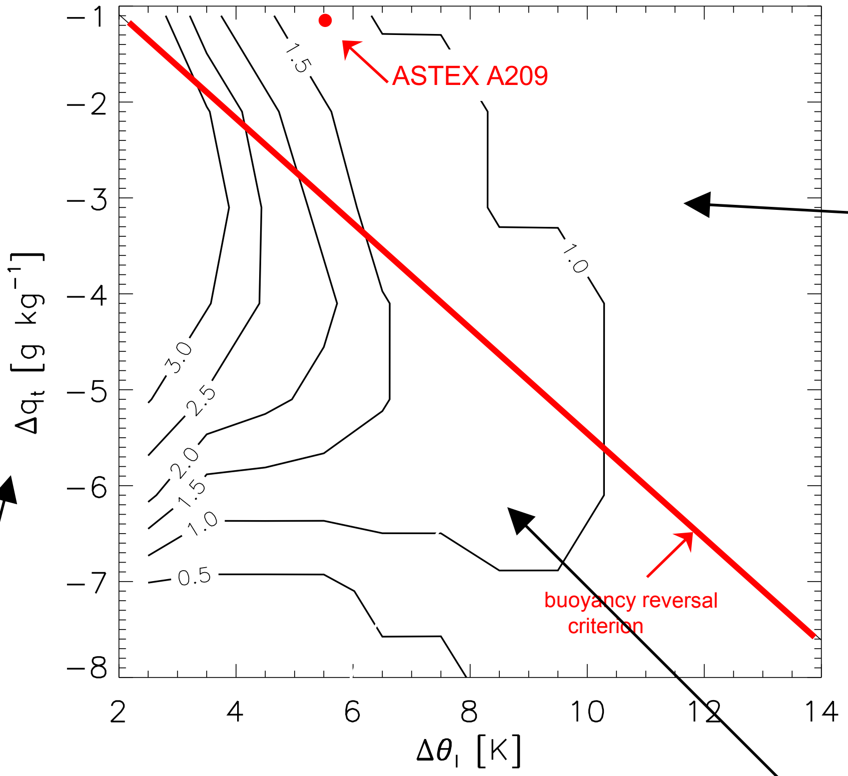
$$\boxed{\overline{w'\theta_v'} = -c_H \sqrt{\overline{E}}\,\ell \left[\sigma\left(A_w \frac{\partial \overline{\theta_l}}{\partial z} + B_w \frac{\partial \overline{q_t}}{\partial z}\right) + (1-\sigma)\left(A_d \frac{\partial \overline{\theta_l}}{\partial z} + B_d \frac{\partial \overline{q_t}}{\partial z}\right)\right]}$$

- ASTEX A209 forcing and initialization

- Δt = 60 s , Δz = 5 m

- Mass flux scheme turned off, no precipitation

Entrainment sensitivity to inversion jumps from a TKE model



slightly larger values than Stage-Businger

entrainment rates decrease in this regime

Entrainment rate depends on moisture jump

many parameterizations predict rates that go to infinity

Conclusions

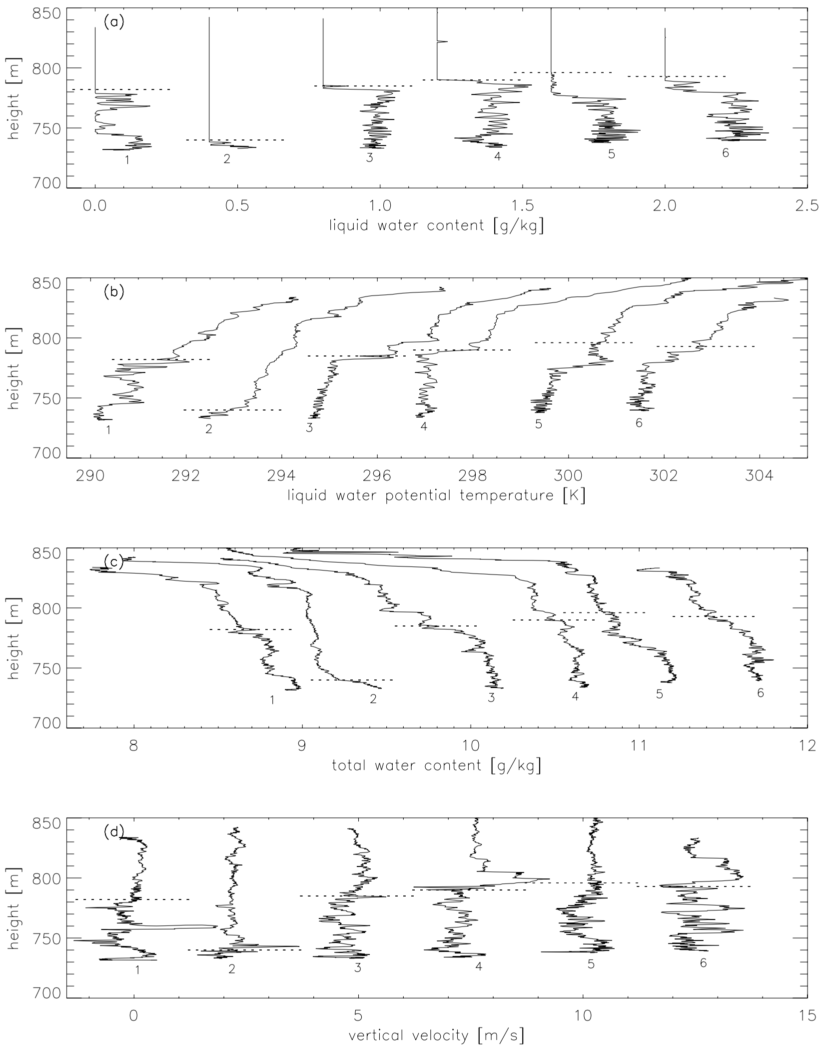
Eddy diffusivity experiments

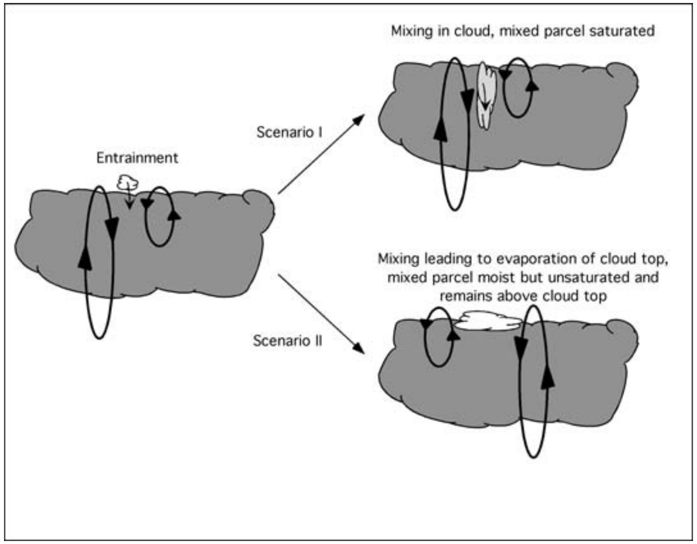
- stratocumulus may dissappear by incorrect BL internal structure, even for 'perfect' entrainment rate

TKE model

- appears to be capable to represent realistic entrainment rates

FIRE I stratocumulus observations of the stratocumulus inversion structure





de Roode and Wang : Do stratocumulus clouds detrain? FIRE I data revisited. BLM, in press

Similar K profiles for heat and moisture - Interpretation

Gradient ratio: $$\frac{\partial\overline{\theta_l}/\partial z}{\partial\overline{q_t}/\partial z} = \frac{\overline{w'\theta_l'}/K}{\overline{w'q_t'}/K} = \frac{H}{LE}\frac{L_v}{c_p}$$ (K drops out)

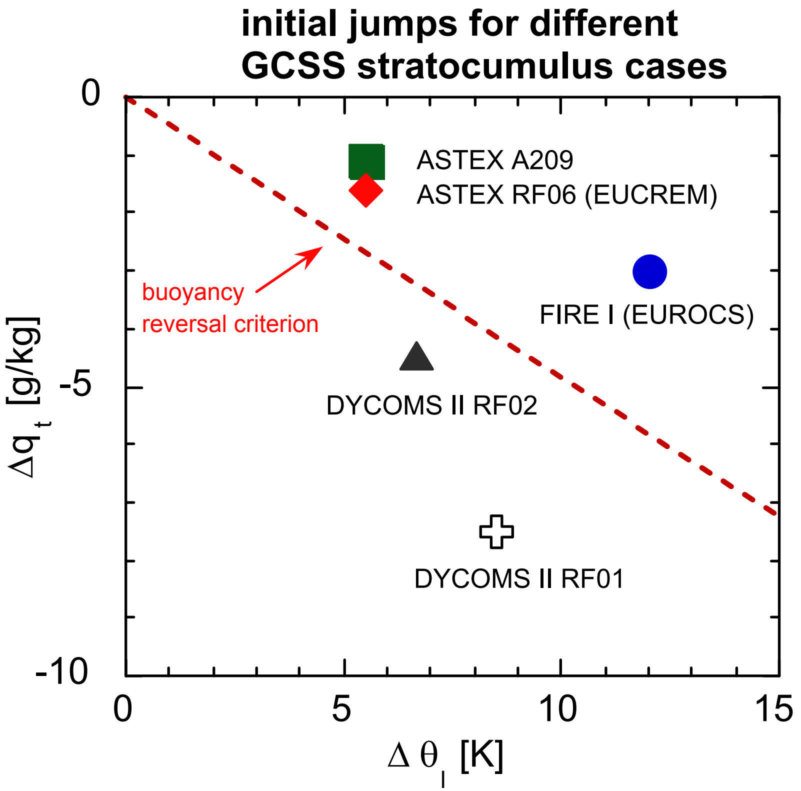
Typical flux values near the surface for marine stratocumulus:

H=10 W/m^2 and LE = 100 W/m^2

Then a 0.1 K decrease in θ_l corresponds to a change of 0.4 g/kg in q_t

The larger the latent heat flux LE, the larger the vertical gradient in q_t will be!

GCSS stratocumulus cases


initial jumps for different GCSS stratocumulus cases

ASTEX A209 boundary conditions

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