The ASTEX Lagrangian model intercomparison case:

LES results

Johan van der Dussen and **Stephan de Roode**

TU Delft, Netherlands

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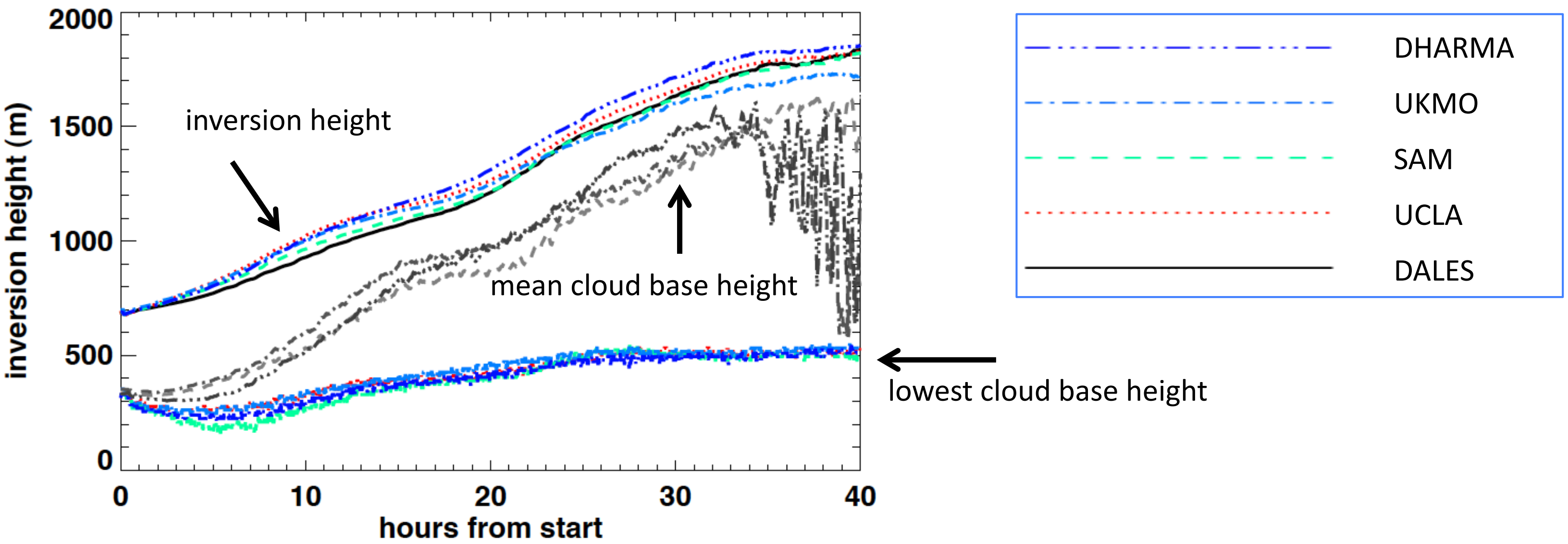
Contents

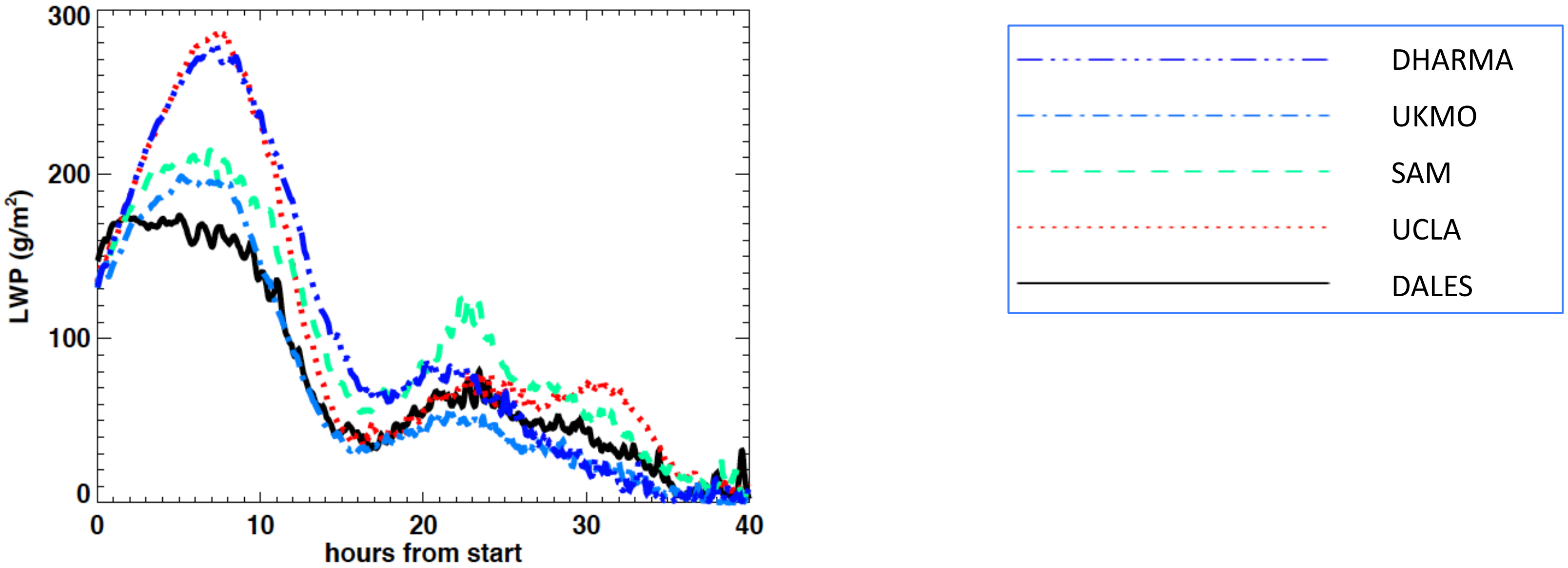
- **Comparison with observations**
  - *Cloud evolution*
  - *Mean state*
  - *Turbulence*
- **LES diagnostics**
  - *Radiation*
- **Subsidence, entrainment and cloud layer depth evolution**
  - *Cloud layer budgets for heat and moisture*

Cloud layer evolution



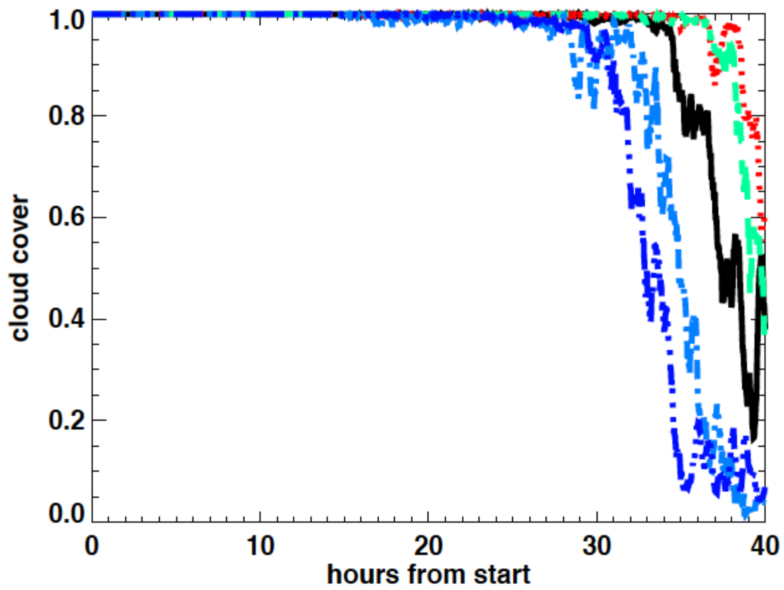
- Bulk evolution similar in different models
- Increasing difference mean and lowest cloud base heights

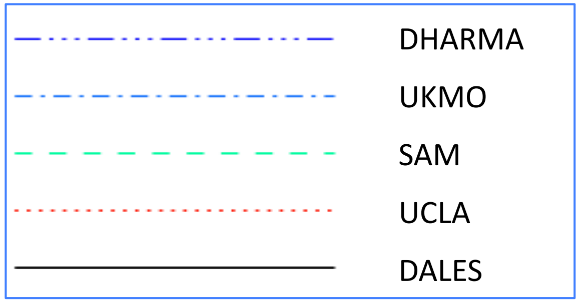
Cloud liquid water path



- **Nearly factor 2 difference in LWP ≈ α $(z_{top}-z_{base})^2$**

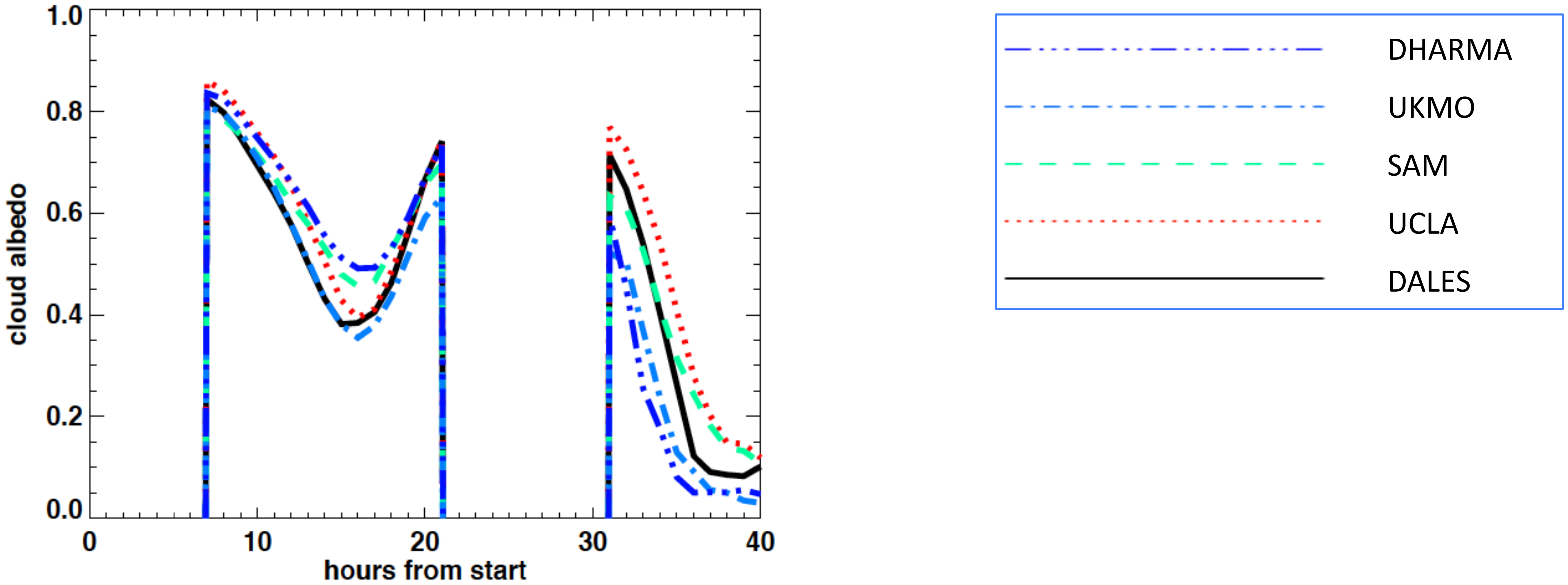
Cloud cover



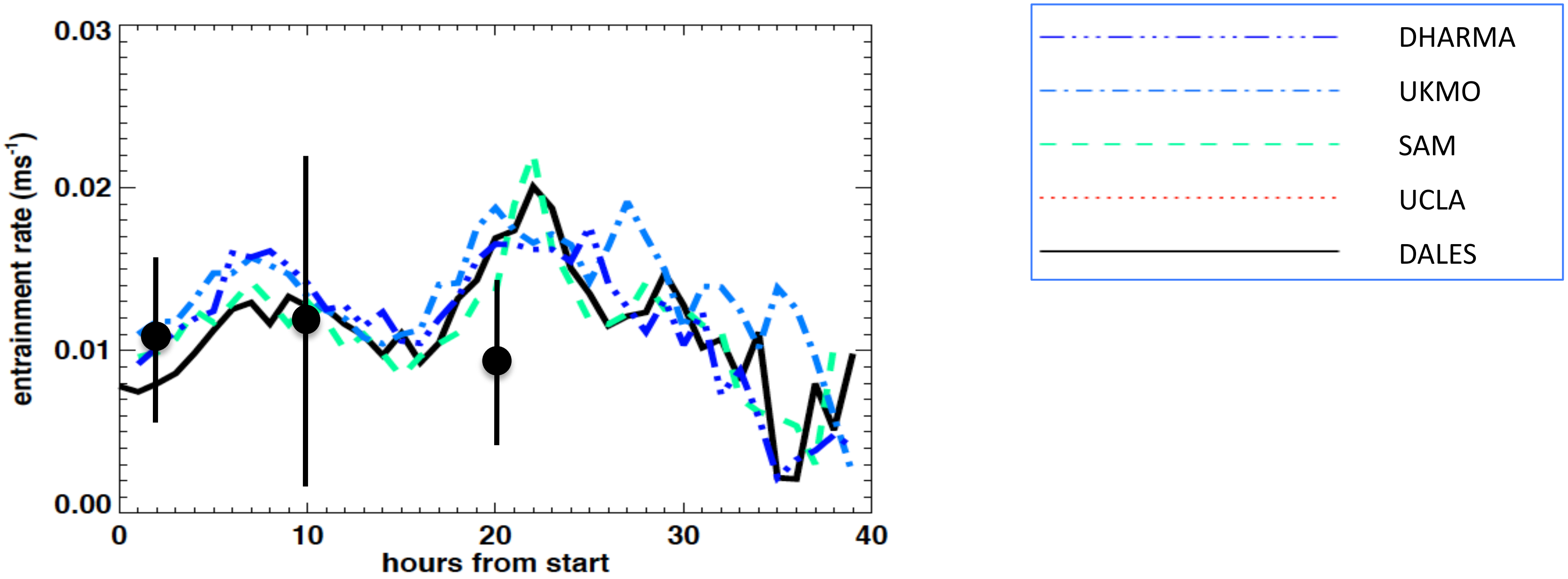


- **Timing of break up differs a couple of hours**

Cloud albedo



Entrainment



- LES entrainment rate varies between 1 and 2 cm/s

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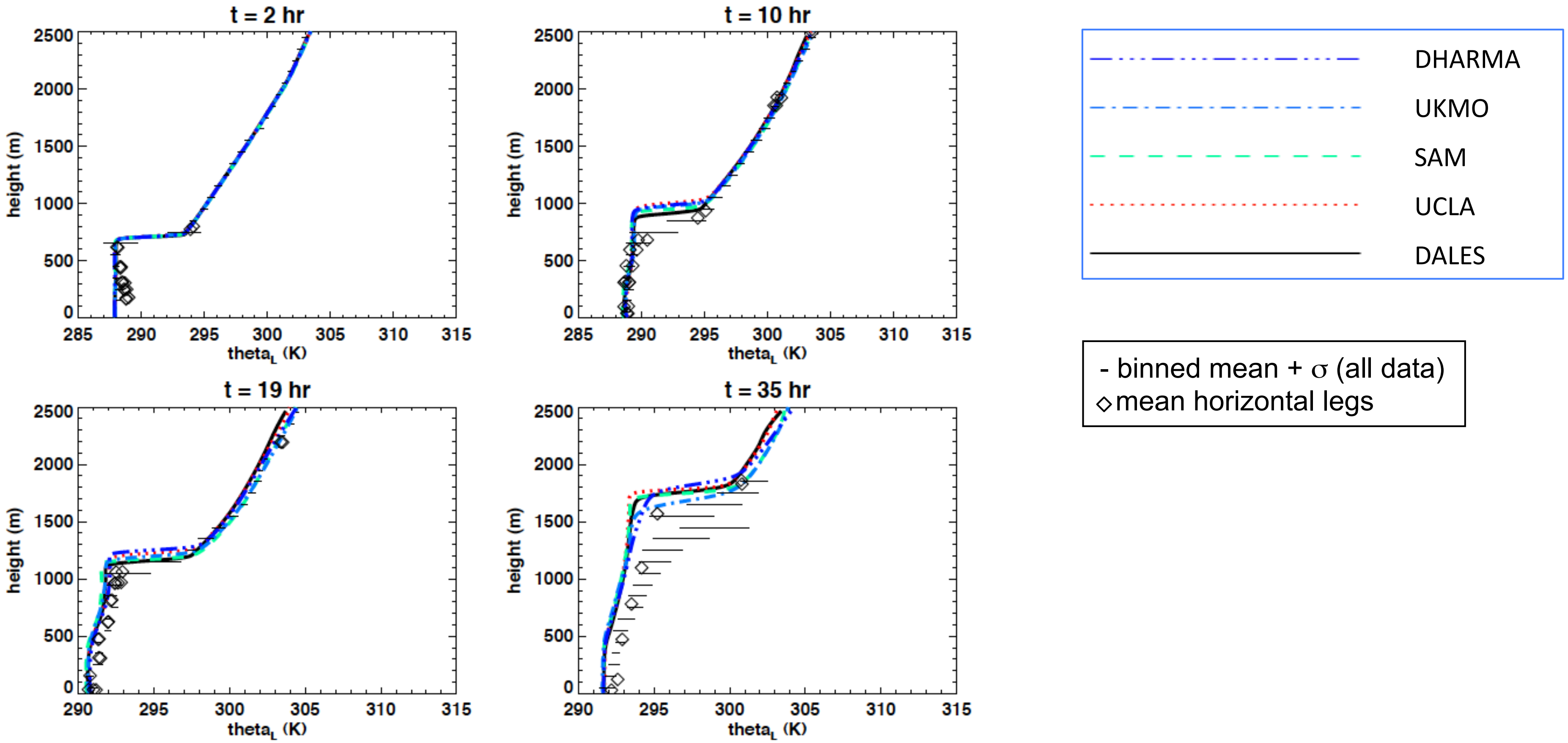
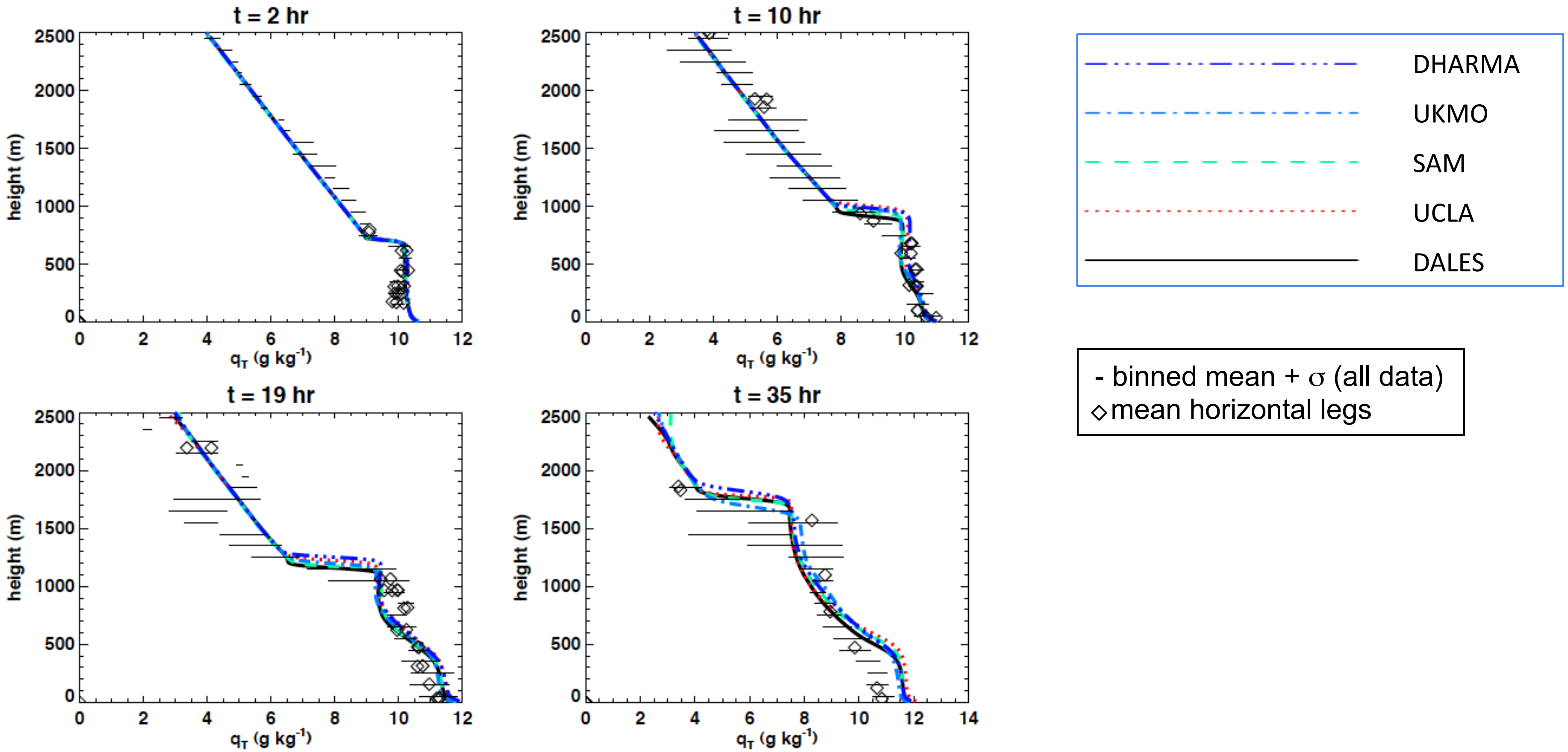
Liquid water potential temperature



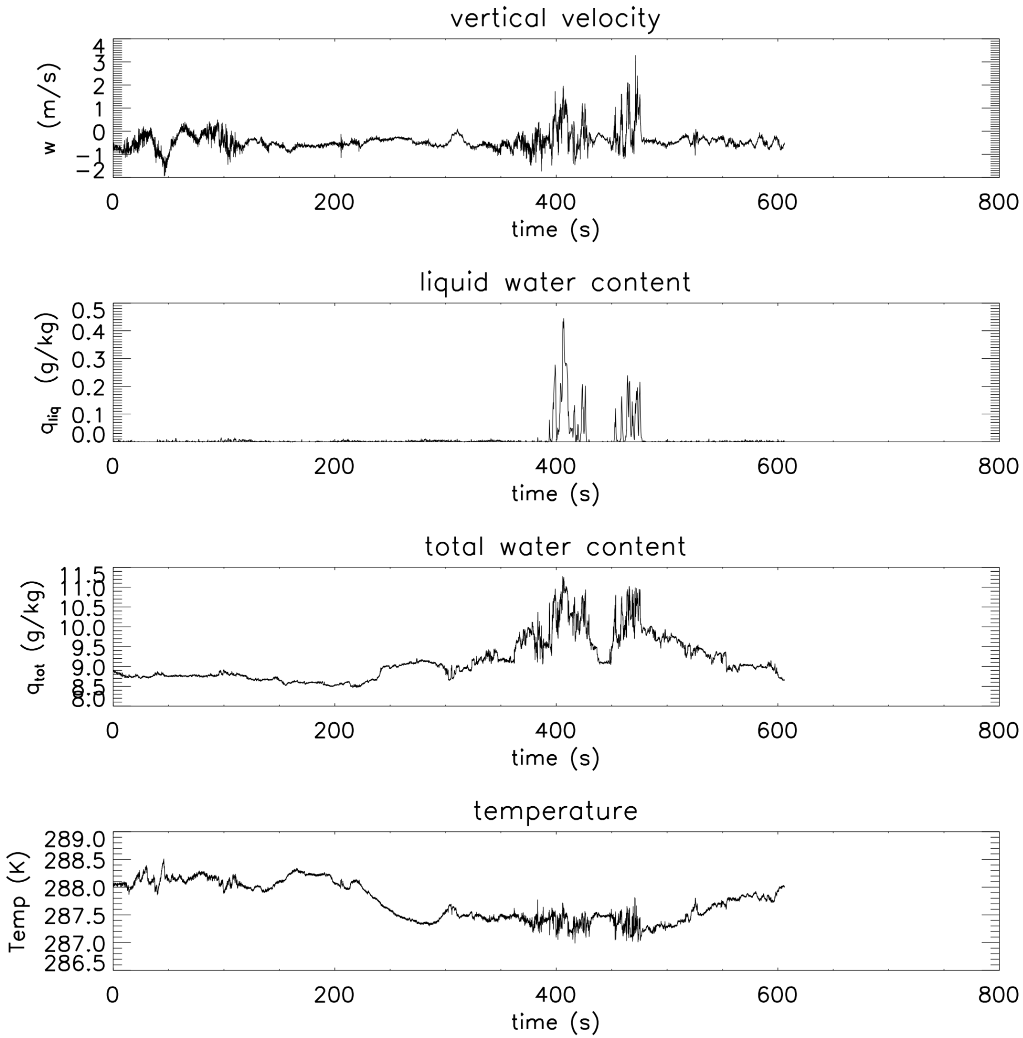
- **Free atmosphere: balance radiative cooling and subsidence warming**
- **Boundary layer too warm at the end of the transition**

Total water content



- Subcloud layer too moist at the end of the transition

Aircraft observations during the 36th hour at 780 m



- **Cumuli present in relatively moist and cold air**
- **Small LES domain cannot represent mesoscale fluctuations**

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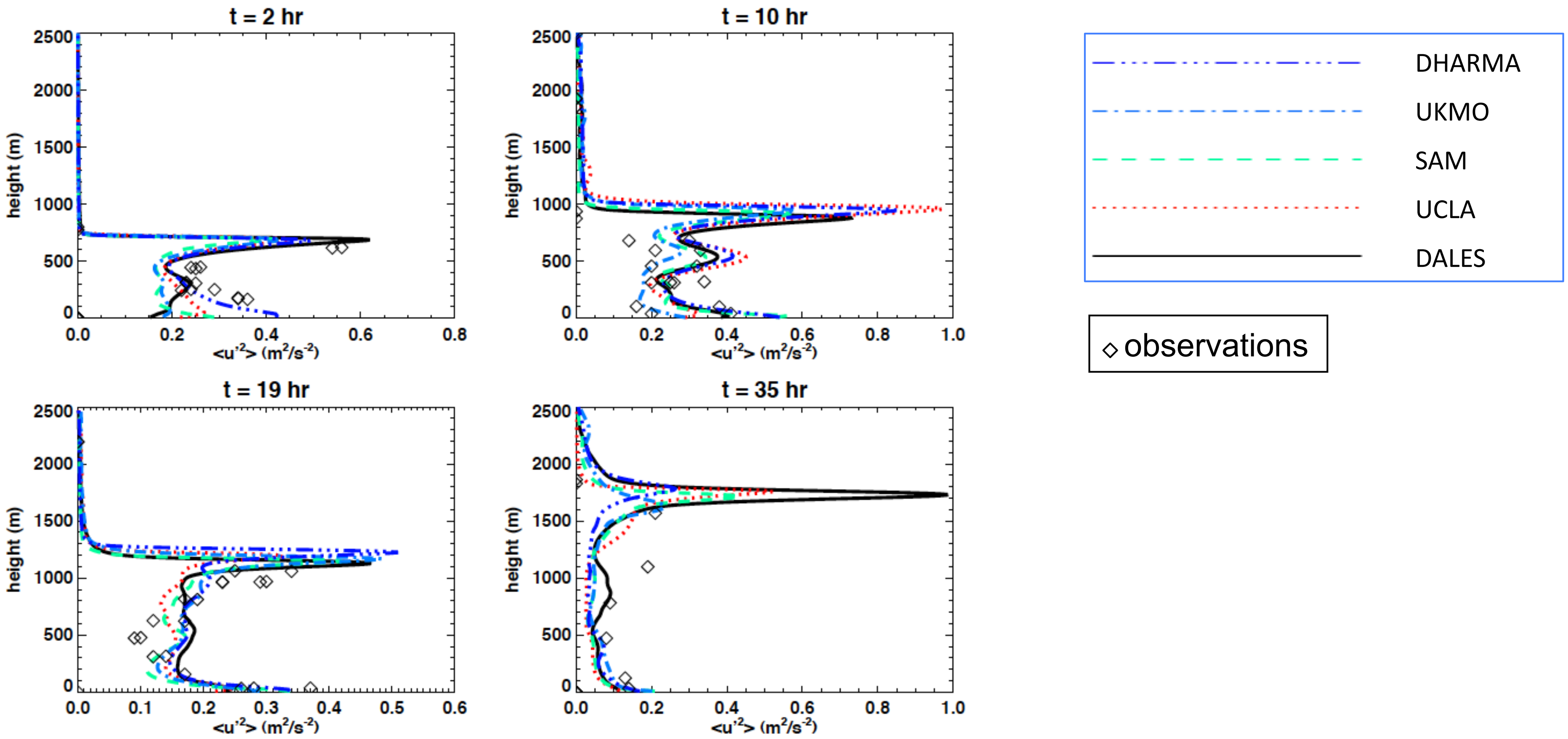
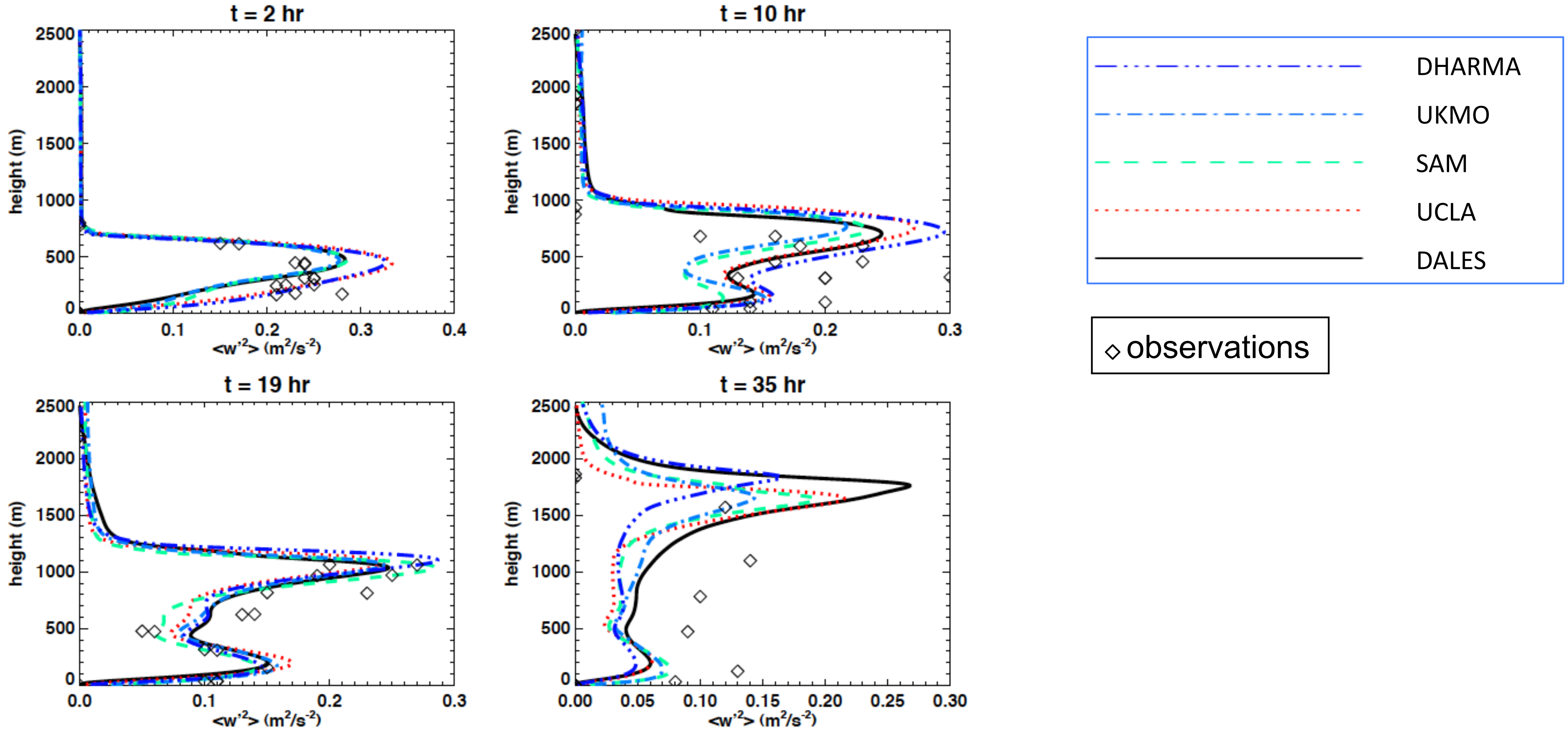
Horizontal wind velocity variance



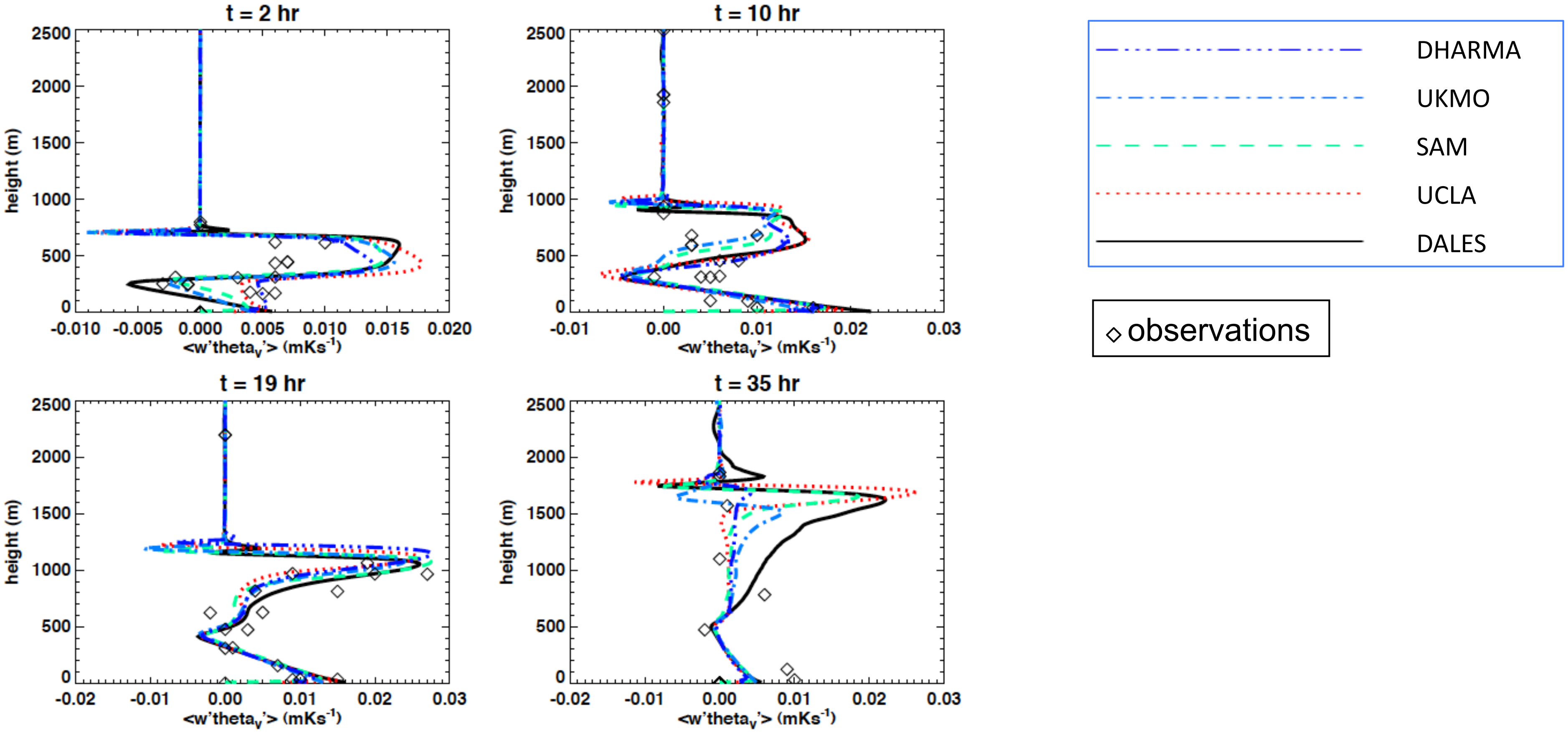
- LES results compare well with observations (running mean filtered, 3.1 km)

Vertical wind velocity variance



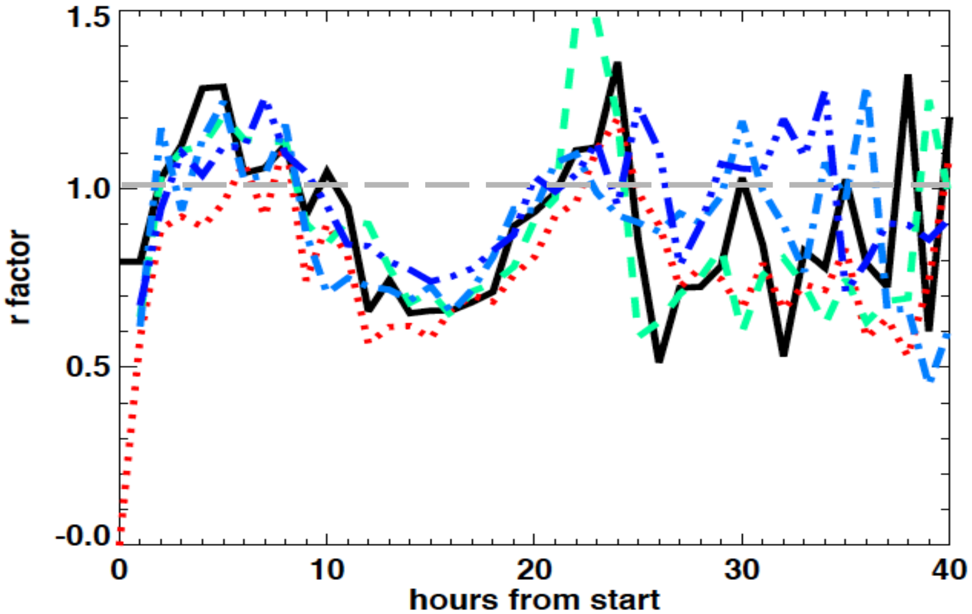
- LES results give double peak structure
- At t=36 hr observations show larger variance

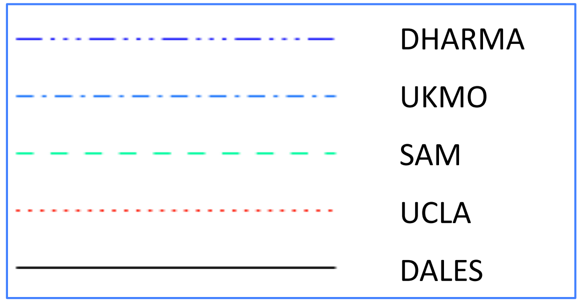
Buoyancy flux



- Good agreement for stratocumulus
- Cumulus results very sensitive to cloud cover

Total specific humidity flux

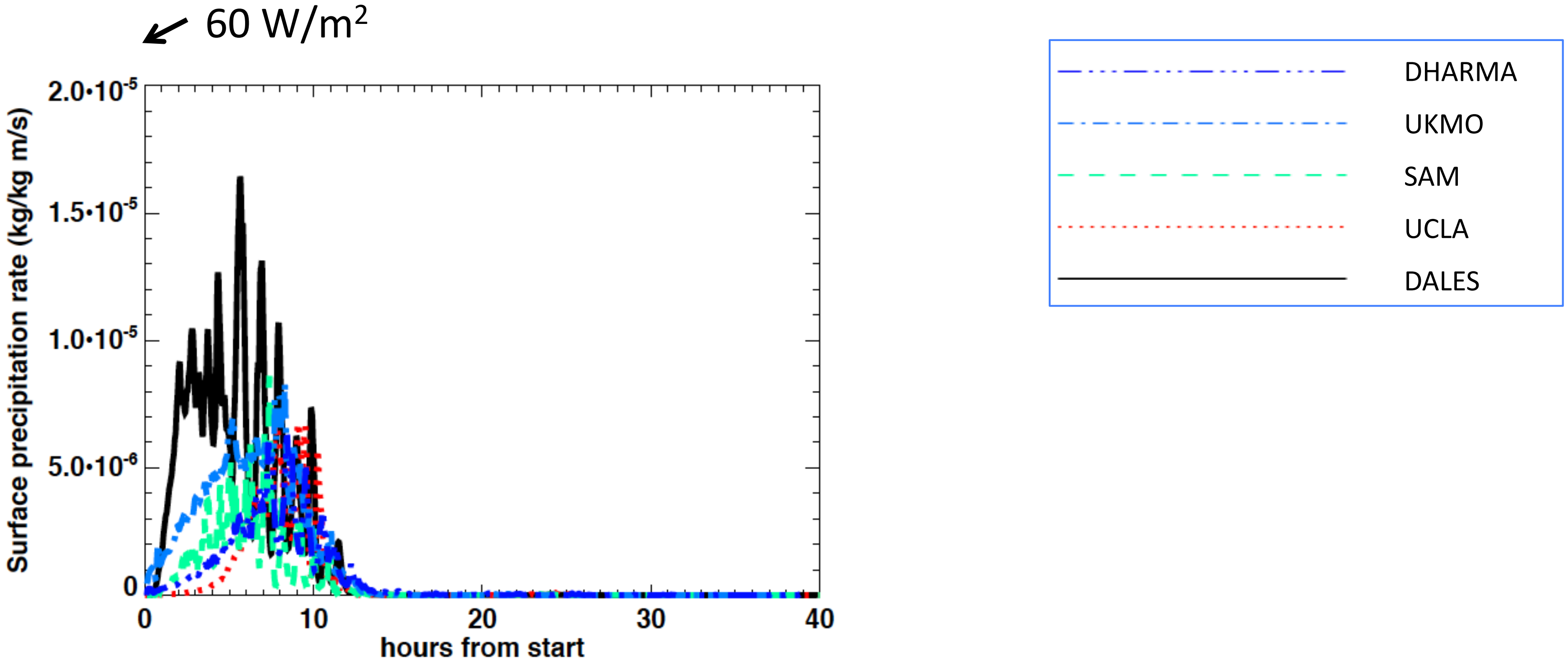




$$r = \frac{\overline{w'q_T'}_{\text{cu base}}}{\overline{w'q_T'}_{\text{sfc}}}$$

r	subcloud layer
r < 1	moistening
r = 1	zero moisture flux divergence
r > 1	drying

Surface precipitation



• *Tekst*

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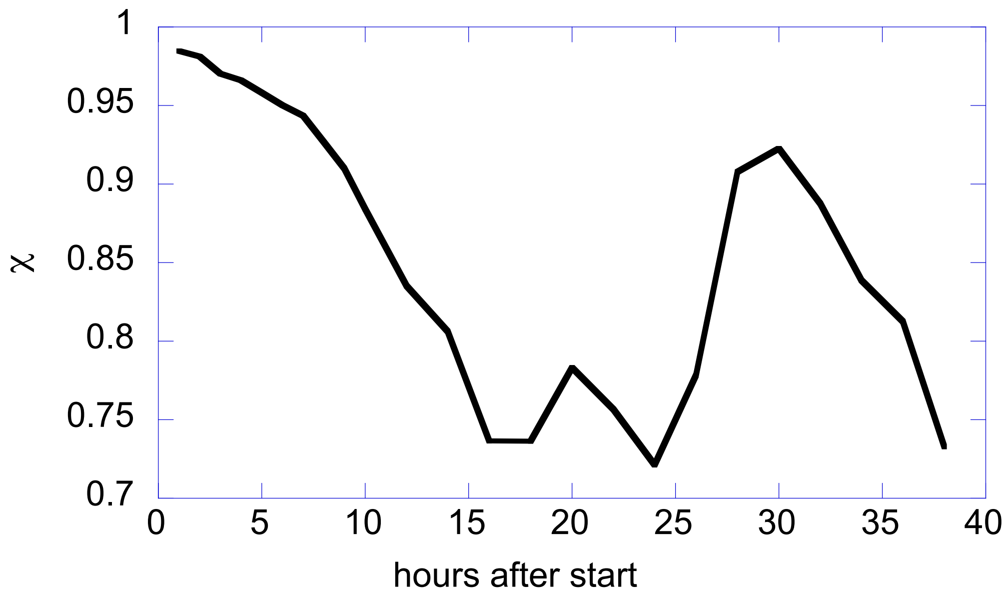
Cloud albedo bias from DALES large domain (25.6x25.6 km^2) results: inhomogeneity factor χ



$\tau_{eff} = \chi\tau$

- Constant solar zenith angle is used to diagnose χ from hourly 3D fields
- Calculation of χ excludes clear air columns

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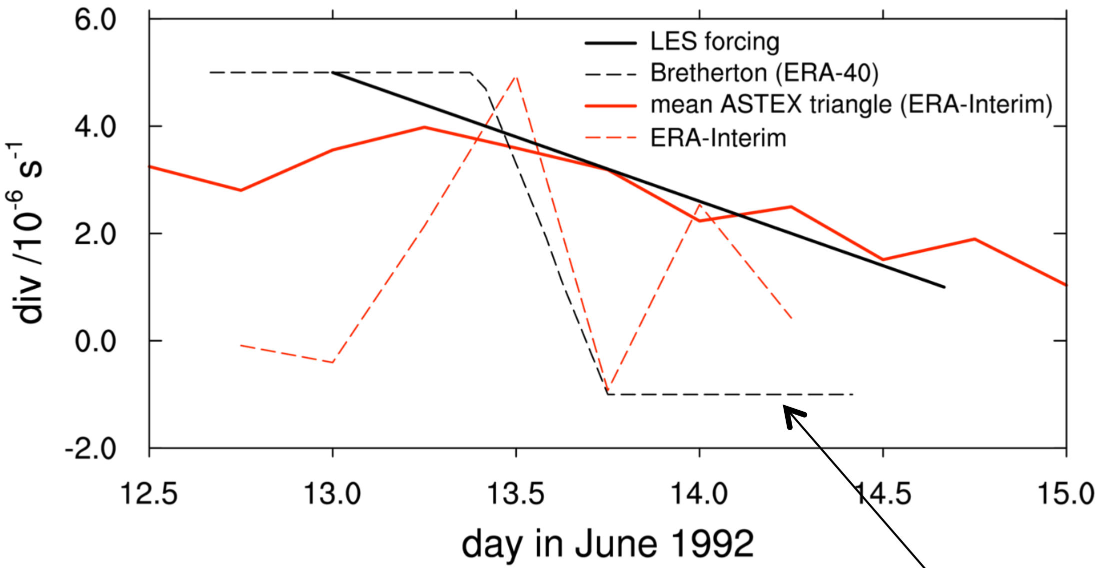
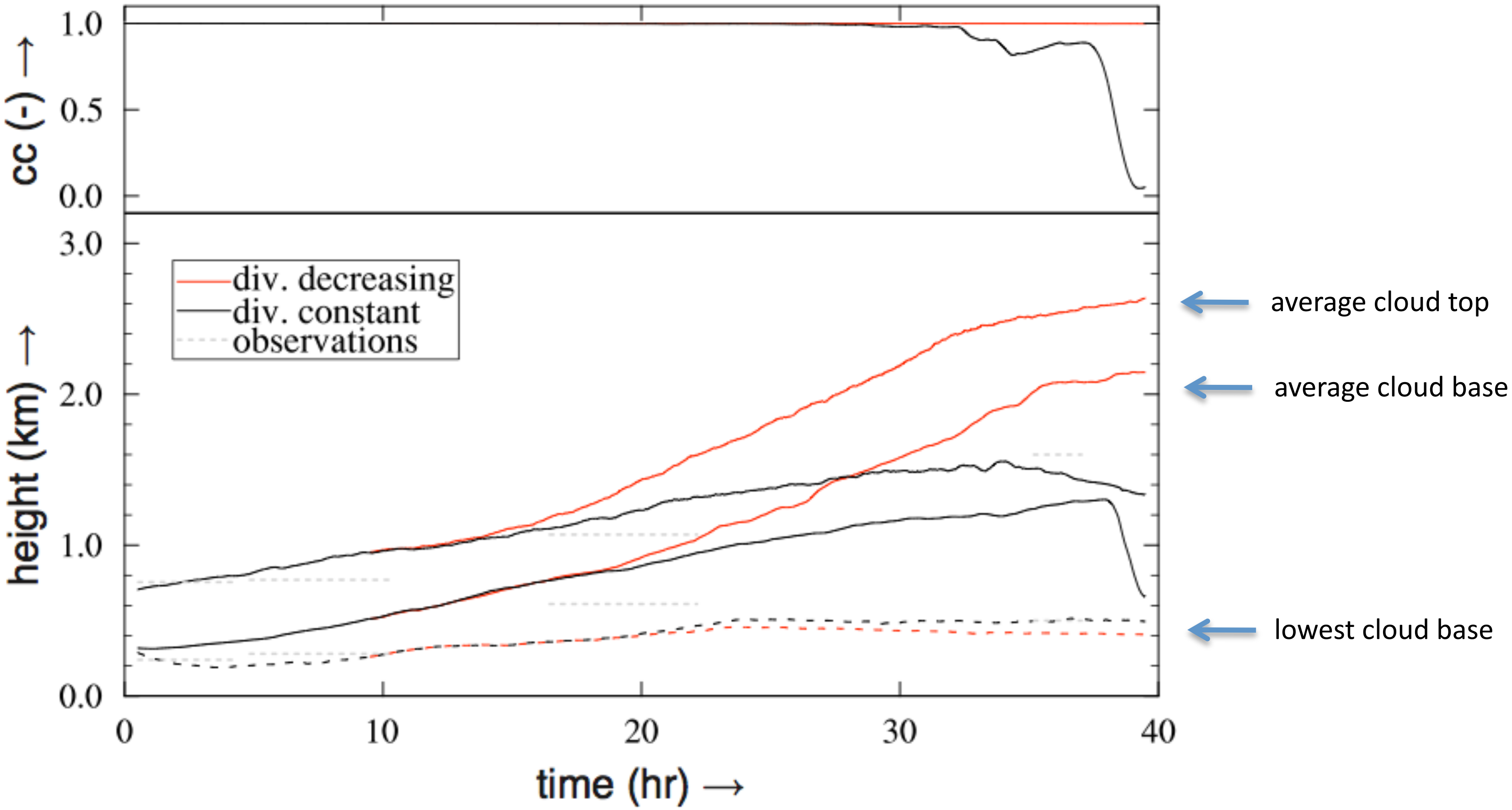
Large-scale divergence



$$\frac{\partial z_{inv}}{\partial t} = \underbrace{w_{subs}}_{-\mathrm{Div}\cdot z_{inv}} + w_{ent}$$

previous round

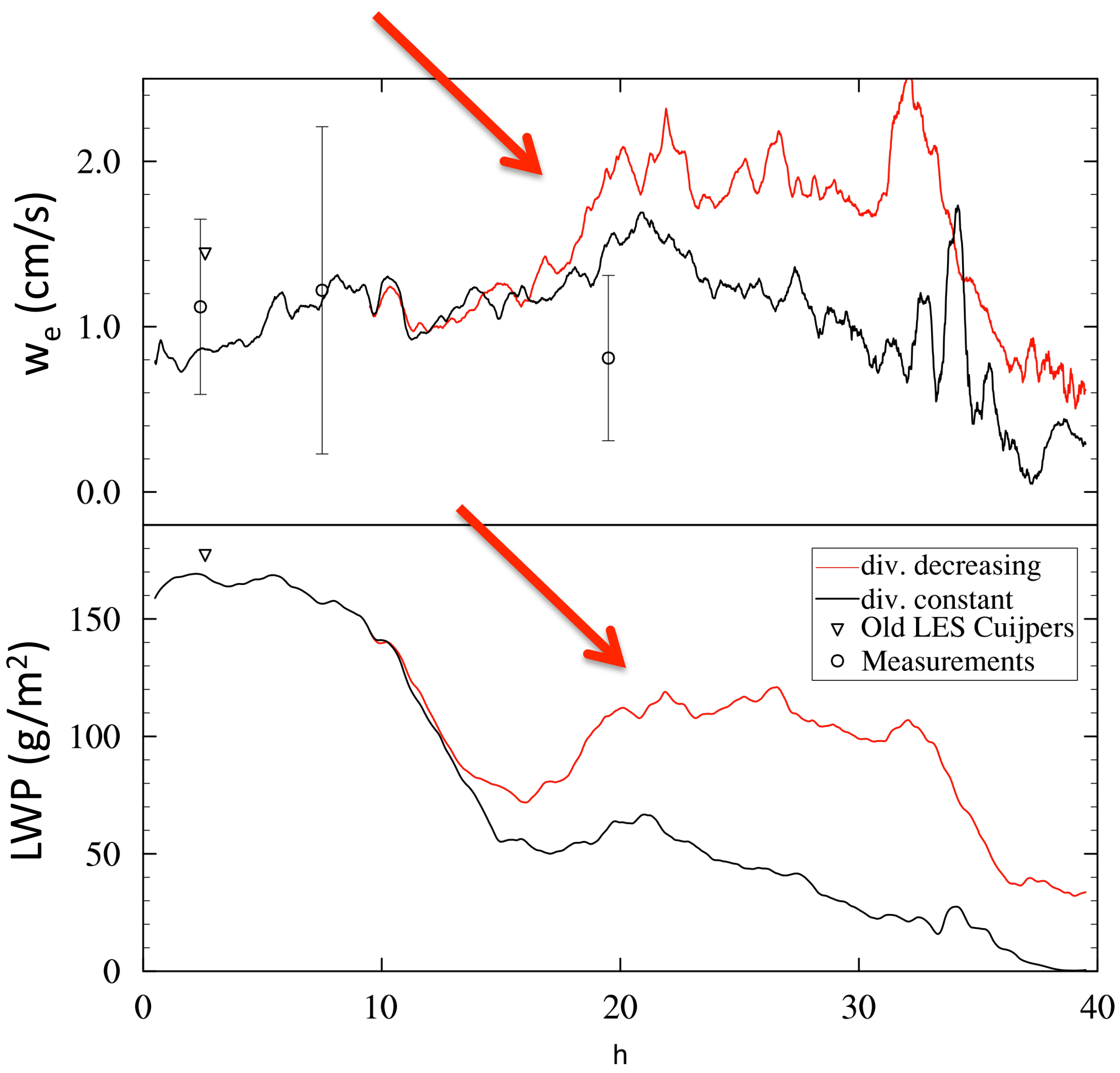
Cloud cover (cc) and cloud boundaries



- Divergence decreasing: deep solid stratocumulus
- Divergence constant: shallow cumulus

Subsidence, entrainment (w_e) and liquid water path (LWP)

weakening subsidence ("upsidence" at the end")



More entrainment, thicker cloud?

Constant divergence (D=5×10^{-6} s^{-1})

stratocumulus dissipates

Tellus (1984), *36A*, 446–457

Stratocumulus cloud deepening through entrainment

By DAVID A. RANDALL, *Goddard Laboratory for Atmospheric Sciences, NASA/Goddard Space Flight Center, Greenbelt, Md 20771, USA*

(Manuscript received February 14; in final form May 8, 1984)

ABSTRACT

It is shown that under a fairly wide range of realistic conditions, stratocumulus cloud-top entrainment actually tends to deepen an existing cloud layer, or tends to produce clouds in an unsaturated mixed layer, even though the entrained air is warmer and drier than the mixed-layer air. These results do not depend on any particular theory of what determines the entrainment rate; they imply that the cloud-top entrainment instability discussed by Randall and Deardorff does not necessarily tend to destroy a layer cloud; it sometimes only makes the cloud deepen. Examples are presented, using the representative soundings of McClatchey et al., the marine-layer data of Neiburger et al., and results from a simulation produced with the UCLA general circulation model.

Entrainment of dry and warm air from above the inversion:

- cloud top height (z_{top}) rises
- cloud base height (z_{base}) rises

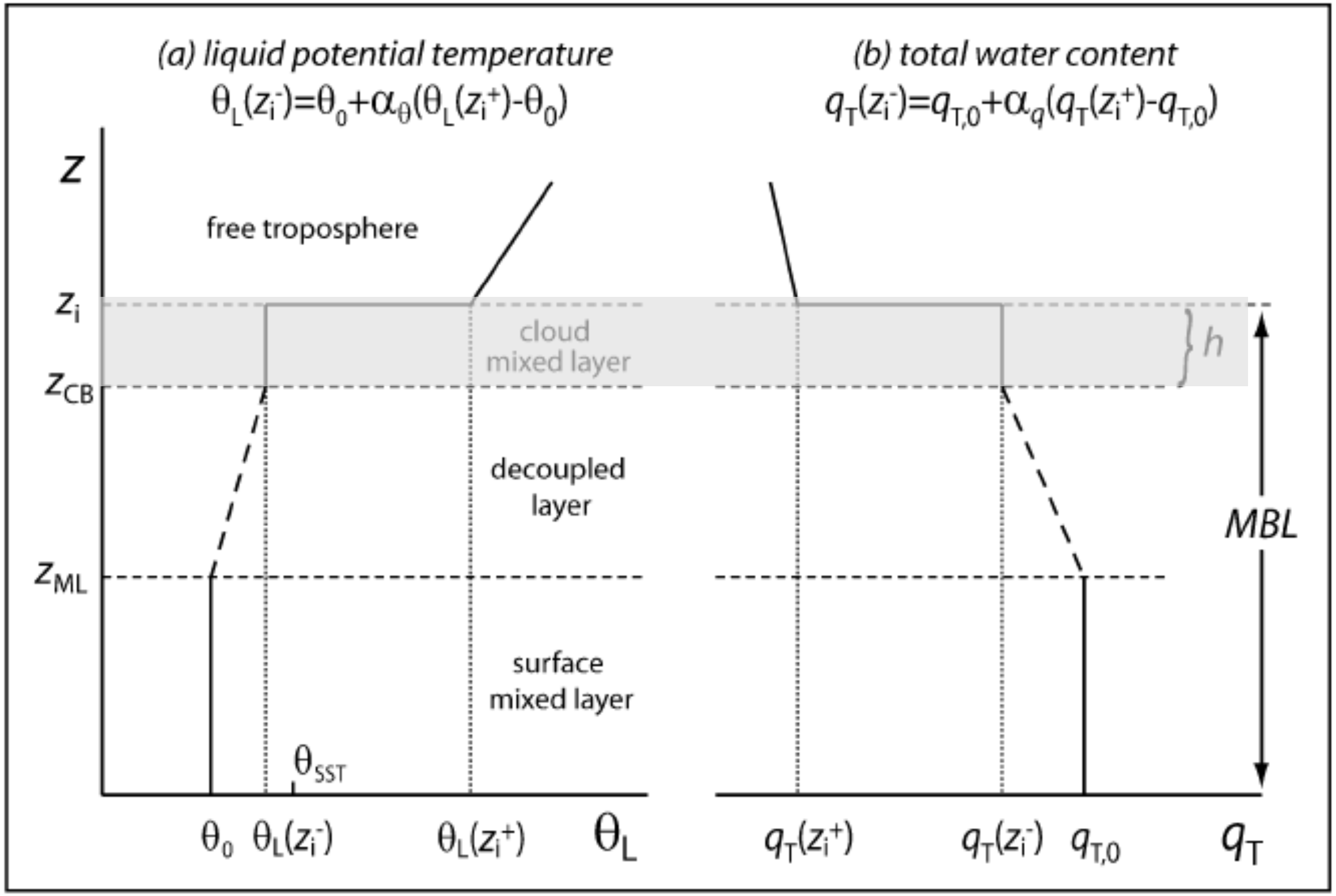
Cloud deepening:

$$\frac{\partial z_{cld}}{\partial t} = \frac{\partial z_{top} - z_{base}}{\partial t} > 0$$

Vertical structure of a stratocumulus cloud layer

15 September 2004 WOOD AND BRETHERTON

calculate heat and moisture budgets for *cloud layer* only



Cloud top height tendency

$$\frac{\partial z_i}{\partial t} = w_e + \overline{w}$$

Inversion height evolution determined by a competition between entrainment and subsidence

Cloud layer depth tendency

$$\frac{\partial z_i}{\partial t} = w_e + \overline{w}$$

Inversion height growth:
competition between entrainment and subsidence

$$\frac{\partial z_{cld}}{\partial t} = \frac{\partial z_i}{\partial t} - \frac{\partial z_{base}}{\partial t}$$

Cloud layer depth growth:
include cloud base height tendency

Cloud base and top height evolution for a well-mixed cloud layer

$$\frac{\partial z_{cld}}{\partial t} = w_e + \overline{w} - \frac{w_e \Delta \overline{q_T} + \overline{w' q_T'}_{z=z_b} - \Delta S_{q_T} - \frac{L_v q_s}{R_v T^2}\left[w_e \Delta \overline{\theta_L} + \overline{w' \theta_L'}_{z=z_b} - \Delta F_{rad} / \left(\rho c_p \right) \right]}{\left(z_i - z_b \right) \left(\frac{\partial q_s}{\partial z} \right)}$$

Cloud base and top height evolution for a well-mixed cloud layer

$$\frac{\partial z_i}{\partial t} = w_e + \overline{w}$$

$$z_{cld} = z_{top} - z_{base}$$

$$\frac{\partial z_{cld}}{\partial t} = w_e + \overline{w} - \frac{w_e \Delta \overline{q_T} + \overline{w' q_T'}_{z=z_b} - \Delta S_{q_T} - \frac{L_v q_s}{R_v T^2}\left[w_e \Delta \overline{\theta_L} + \overline{w' \theta_L'}_{z=z_b} - \Delta F_{rad} / (\rho c_p)\right]}{(z_i - z_b)\left(\frac{\partial q_s}{\partial z}\right)}$$

Cloud layer depth increases by entrainment

Cloud base and top height evolution for a well-mixed cloud layer

$$\frac{\partial z_i}{\partial t} = w_e + \overline{w}$$

$$z_{cld} = z_{top} - z_{base}$$

$$\frac{\partial z_{cld}}{\partial t} = w_e + \overline{w} - \frac{w_e \Delta \overline{q_T} + \overline{w' q_T'}_{z=z_b} - \Delta S_{q_T} - \frac{L_v q_s}{R_v T^2}\left[w_e \Delta \overline{\theta_L} + \overline{w' \theta_L'}_{z=z_b} - \Delta F_{rad} / (\rho c_p) \right]}{(z_i - z_b)\left(\frac{\partial q_s}{\partial z}\right)}$$

Entrainment drying – Cloud layer thins

Entrainment warming – Cloud layer thins

Cloud base and top height evolution for a well-mixed cloud layer

$$\frac{\partial z_i}{\partial t} = w_e + \overline{w}$$

$$z_{cld} = z_{top} - z_{base}$$

$$\frac{\partial z_{cld}}{\partial t} = w_e + \overline{w} - \frac{w_e \Delta \overline{q_T} + \overline{w' q_T'}_{z=z_b} - \Delta S_{q_T} - \frac{L_v q_s}{R_v T^2}\left[w_e \Delta \overline{\theta_L} + \overline{w' \theta_L'}_{z=z_b} - \Delta F_{rad} / \left(\rho c_p \right) \right]}{\left(z_i - z_b \right)\left(\frac{\partial q_s}{\partial z} \right)}$$

Subsidence - Cloud thinning

"Upsidence" - Cloud thickening

Cloud base and top height evolution for a well-mixed cloud layer

$$\frac{\partial z_i}{\partial t} = w_e + \overline{w}$$

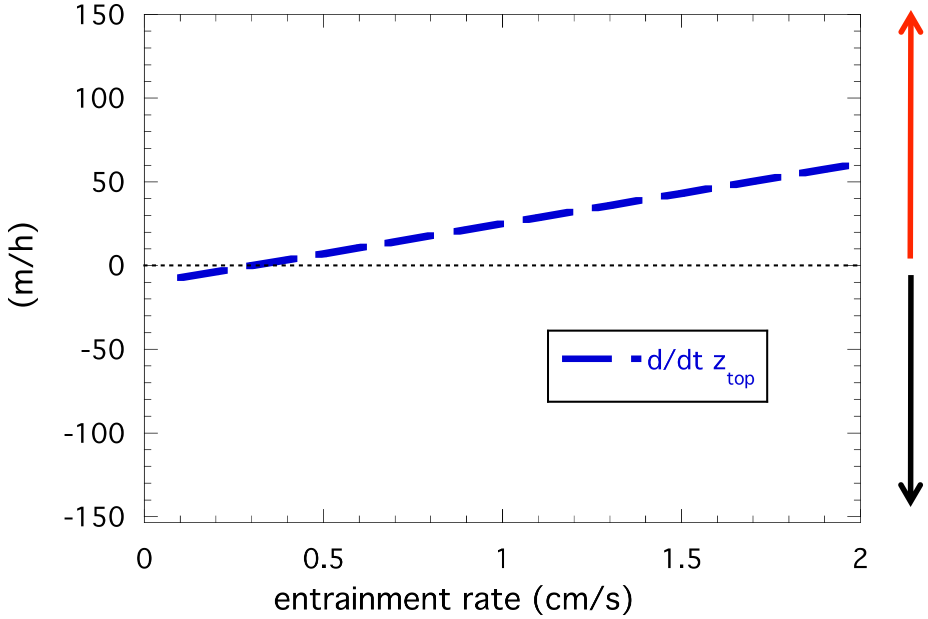
$$z_{cld} = z_{top} - z_{base}$$

$$\frac{\partial z_{cld}}{\partial t} = w_e + \overline{w} - \frac{w_e \Delta \overline{q_T} + \overline{w' q_T'}_{z=z_b} - \Delta S_{q_T} - \frac{L_v q_s}{R_v T^2}\left[w_e \Delta \overline{\theta_L} + \overline{w' \theta_L'}_{z=z_b} - \Delta F_{rad} / \left(\rho c_p\right)\right]}{\left(z_i - z_b\right)\left(\frac{\partial q_s}{\partial z}\right)}$$

Moistening –
Cloud thickening

Rad cooling –
Cloud thickening

Cloud base and top height evolution for ASTEX as a function of the entrainment rate



$w_e > -w_{subs}$

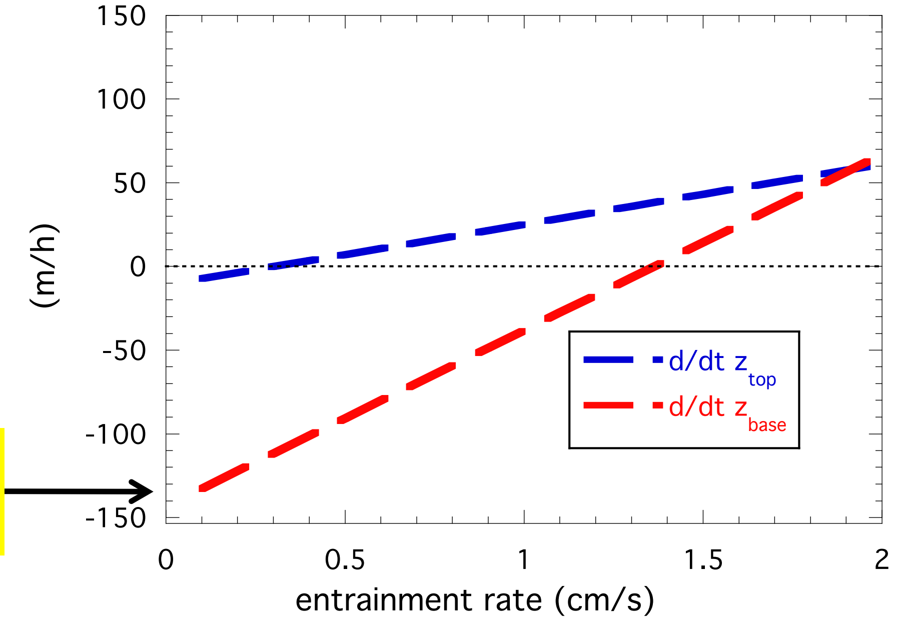
Cloud top increases

$w_e < -w_{subs}$

Cloud top goes down

$\rho c_p \langle w'\theta_L' \rangle_{zbase}$ = 11 W/m^2 , $\rho L_v \langle w'q_T' \rangle_{zbase}$ = 60 W/m^2
$\Delta\theta_L$ = 5 K , Δq_T = -1.1 g/kg
ΔLW = 74 W/m^2
Div = 5 x 10^{-6} s^{-1}
z_{base} = 300 m , z_{top} = 600 m

Cloud base and top height evolution for ASTEX as a function of the entrainment rate

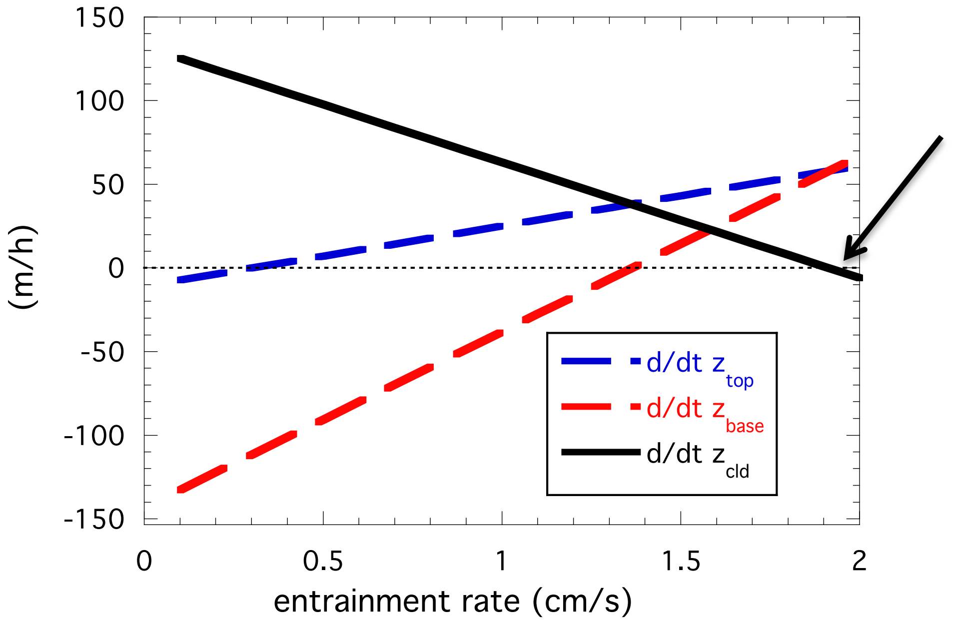


$w_e = 0$

Cloud base goes down

$\rho c_p \langle w'\theta_L' \rangle_{zbase}$	$= 11\ W/m^2$	, $\rho L_v \langle w'q_T' \rangle_{zbase}$	$= 60\ W/m^2$
$\Delta\theta_L$	$= 5\ K$	, Δq_T	$= -1.1\ g/kg$
ΔLW	$= 74\ W/m^2$		
Div	$= 5 \times 10^{-6}\ s^{-1}$		
z_{base}	$= 300\ m$	, $z_{top} = 600\ m$	

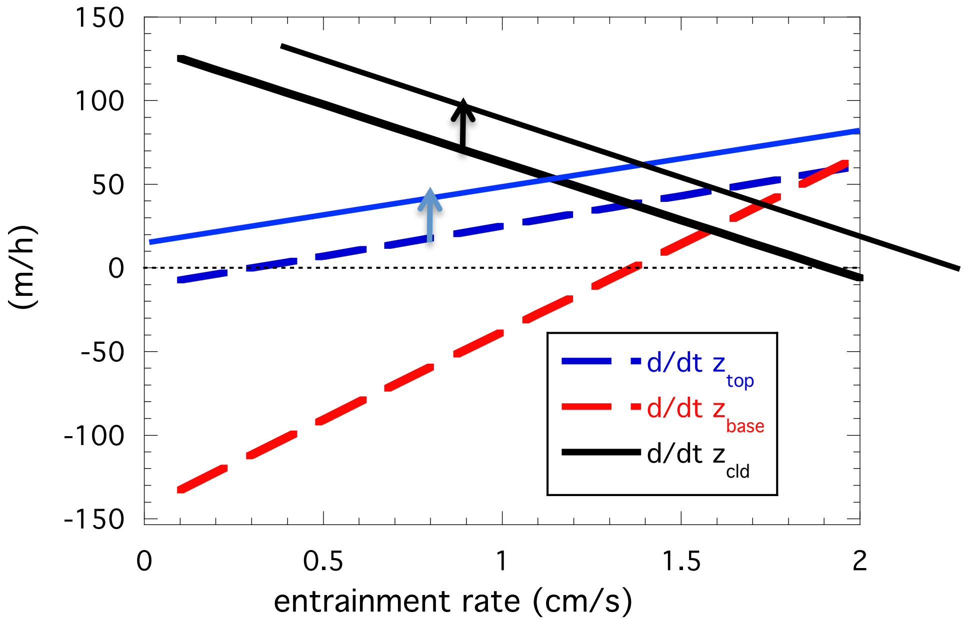
Cloud base and top height evolution for ASTEX as a function of the entrainment rate



w_{ent} < 1.9 cm/s

cloud layer depth increases

Decrease subsidence:
more entrainment is needed to make cloud thinner



Main conclusions

LES captures cloud evolution quite well

Stratocumulus cloud top increases, cumulus cloud base at top subcloud layer

Mean state:

Deviation in temperature and humidity during last part of transition

LES cannot represent mesoscale

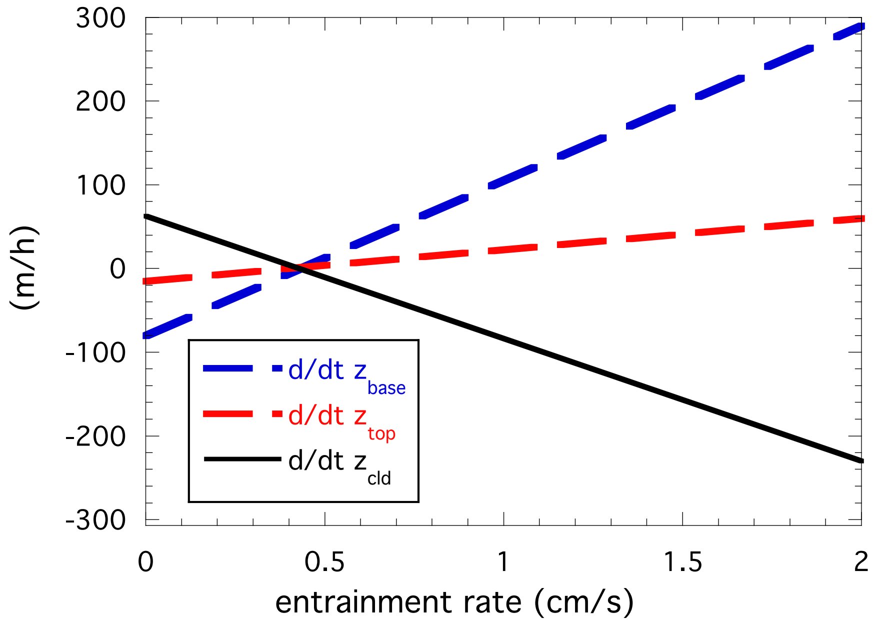
Decoupling

Cumulus clouds transport moisture from the subcloud to the cloud layer

Subsidence and entrainment

For rather large entrainment rates (~ 2 cm/s) stratocumulus cloud layer can grow

Example: DYCOMS II RF01

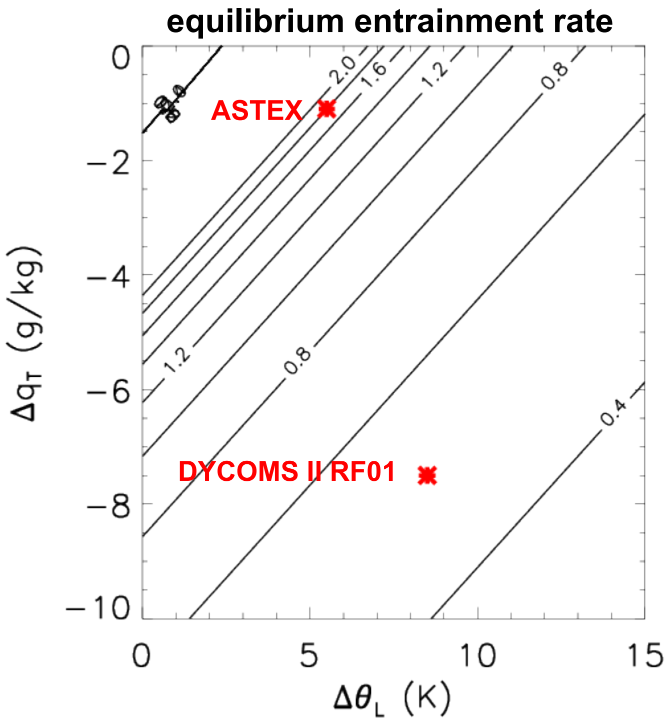


For w_{ent} > 0.4 cm/s,

cloud layer rapidly thins

$\rho c_p \langle w'\theta_L' \rangle_{zbase}$	= 11 W/m^2	, $\rho L_v \langle w'q_T' \rangle_{zbase}$	= 60 W/m^2
$\Delta\theta_L$	= 8.5 K	, Δq_T	= -7.5 g/kg
ΔLW	= 74 W/m^2		
Div	= 5 x 10^{-6} s^{-1}		
z_{base}	= 500 m	, z_{top}= 800 m	

Steady-state cloud layer depth: equilibrium entrainment rates



$\rho c_p \langle w'\theta_L' \rangle_{zbase}$ = 11 W/m^2 , $\rho L_v \langle w' q_T' \rangle_{zbase}$ = 80 W/m^2

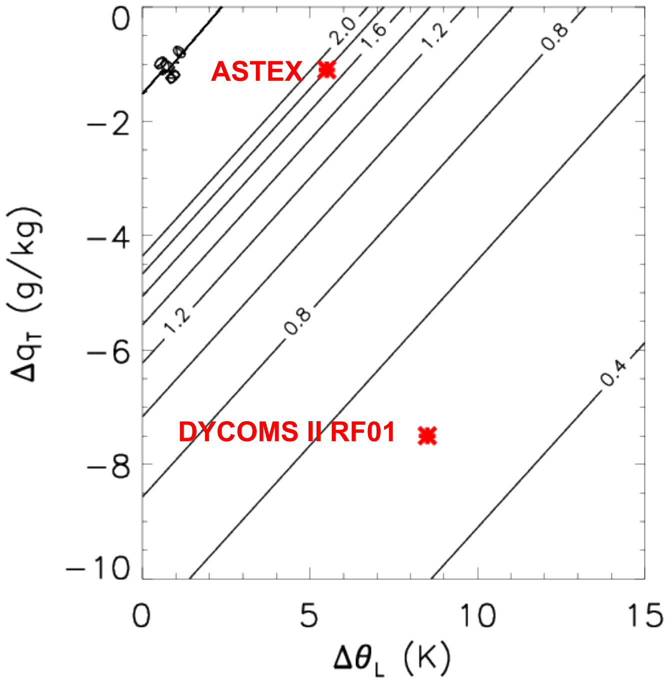
ΔLW = 70 W/m^2

Div = 5 x 10^{-6} s^{-1}

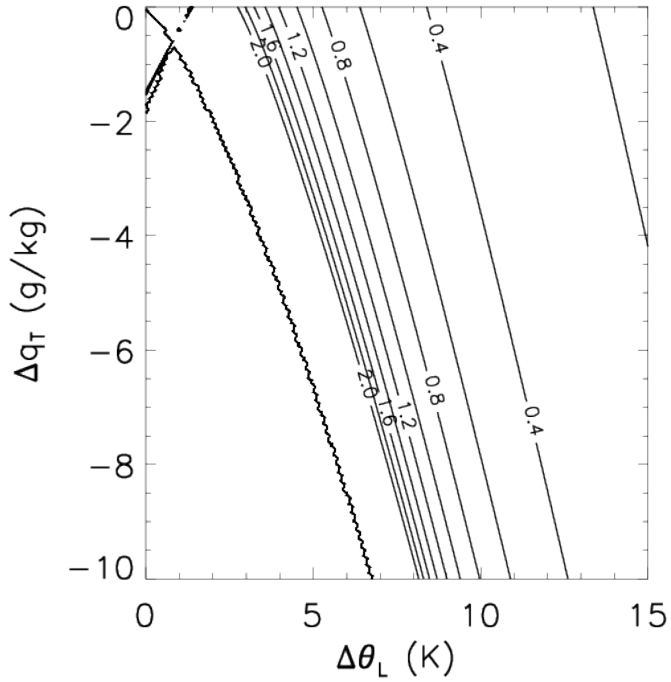
z_{base} = 300 m , z_i= 650 m

Steady-state cloud layer depth: equilibrium entrainment rates

equilibrium entrainment rate



entrainment rate (parameterization by Nicholls and Turton, 1986)



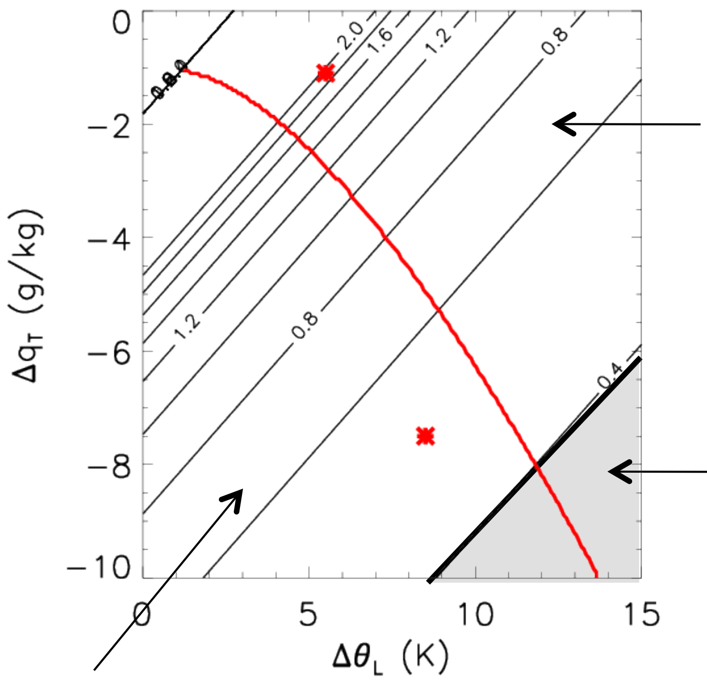
$\rho c_p \langle w'\theta_L' \rangle_{zbase} = 11\ \mathrm{W/m^2}$, $\rho L_v \langle w'q_T' \rangle_{zbase} = 80\ \mathrm{W/m^2}$

$\Delta LW = 70\ \mathrm{W/m^2}$

$\mathrm{Div} = 5 \times 10^{-6}\ \mathrm{s^{-1}}$

$z_{base} = 300\ \mathrm{m}$, $z_i = 650\ \mathrm{m}$

Regimes of cloud layer growth rates



Cloud layer thickens
Cloud top height increases

Cloud top height decreases
(entrainment smaller than subsidence)

Cloud layer thins
Cloud top height increases