# Modelling and Parameterizing the Cloudy Boundary Layer:

## A GCSS-inspired Overview

A. Pier Siebesma

siebesma@knmi.nl

Climate Research Department

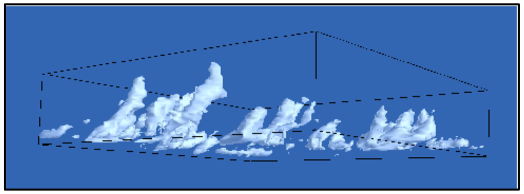
Royal Netherlands Meteorological Institute (KNMI)

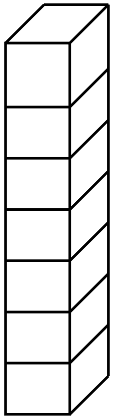
De Bilt, The Netherlands

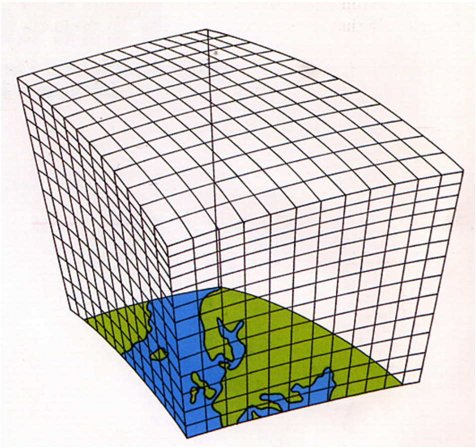
KNMI

Photo courtesy Bjorn Stevens

# (Simplified) Working Strategy of GEWEX Cloud System Studies (GCSS)







Large Eddy Simulation (LES) Models

Cloud Resolving Models (CRM)

Single Column Model

Versions of Climate Models

3d-Climate Models

NWP's

Observations from Field Campaigns

Global observational Data sets

**Development**

**Testing**

**Evaluation**

# Organization of GCSS

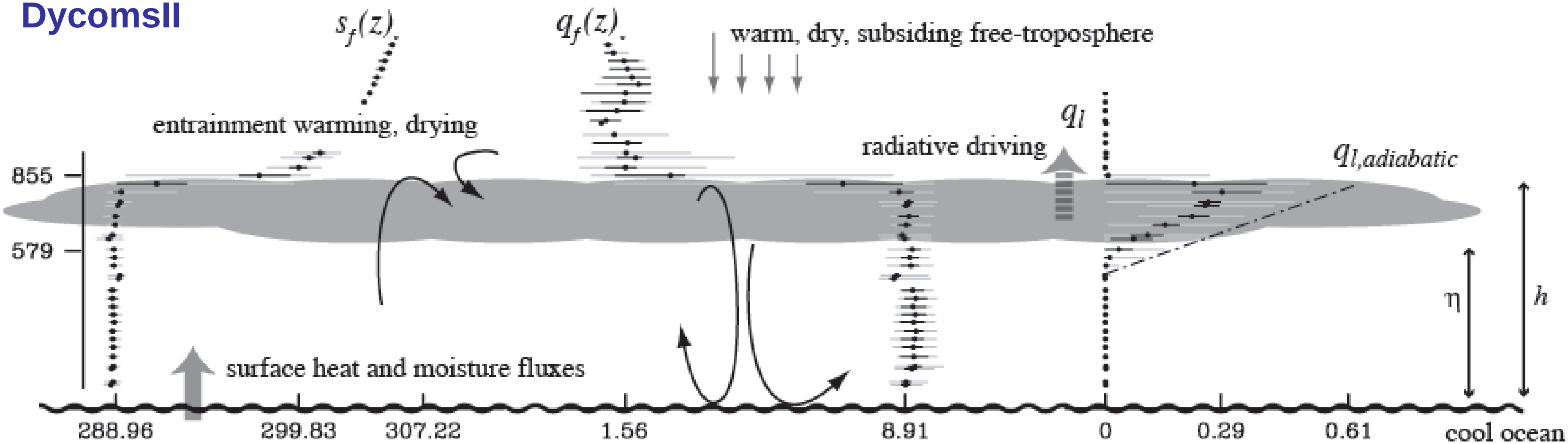
Organized thematically in working groups around different cloud types:

(1) boundary layer clouds, more info www.knmi.nl/~siebesma
(2) cirrus,
(3) extra tropical cloud systems
(4) deep convective cloud systems
(5) polar clouds

# Stratocumulus : characteristics and used variables

Courtesy : Bjorn Stevens

**DycomsII**



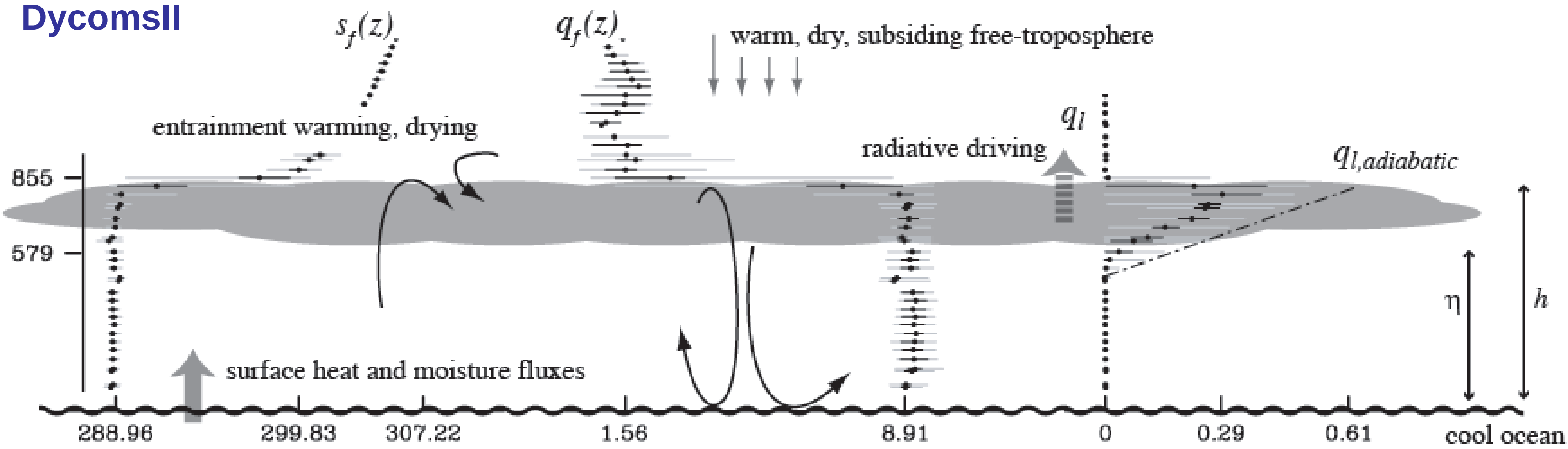

**Computation of the flux:** $\overline{w'\psi'} = -K_\psi \frac{\partial \overline{\psi}}{\partial z}$

**Variables to be used: moist conserved variables:** $\psi \in \{q_t, \theta_l\}$

# Stratocumulus : characteristics and used variables

Courtesy : Bjorn Stevens

## DycomsII



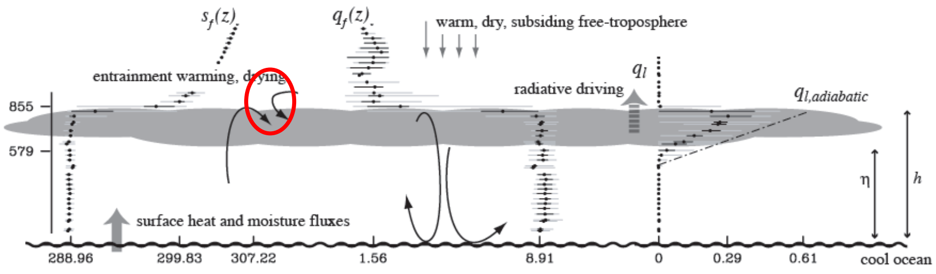

**Computation of the flux:** $$\overline{w'\psi'} = -K_\psi \frac{\partial \overline{\psi}}{\partial z}$$

**Variables to be used: moist conserved variables:** $$\psi \in \{q_t, \theta_l\}$$

Remark: Allthough seemingly trivial, it is only since the last couple of years that ECMWF and HIRLAM have switched to a mixing schemes which is formulated are moist conserved variables.

# Stratocumulus : Top-entrainment (1)

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




**Representation of entrainment rate $w_e$**

1. K-profile $\quad K = w_e\, \Delta z \quad , \quad w_e$ from parametrization

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

**Question**

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

# Stratocumulus : Top-entrainment (2)
# Prescribed entrainment parameterization

- Nicholls and Turton (1986)

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

- 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)

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

- Lock (1998)

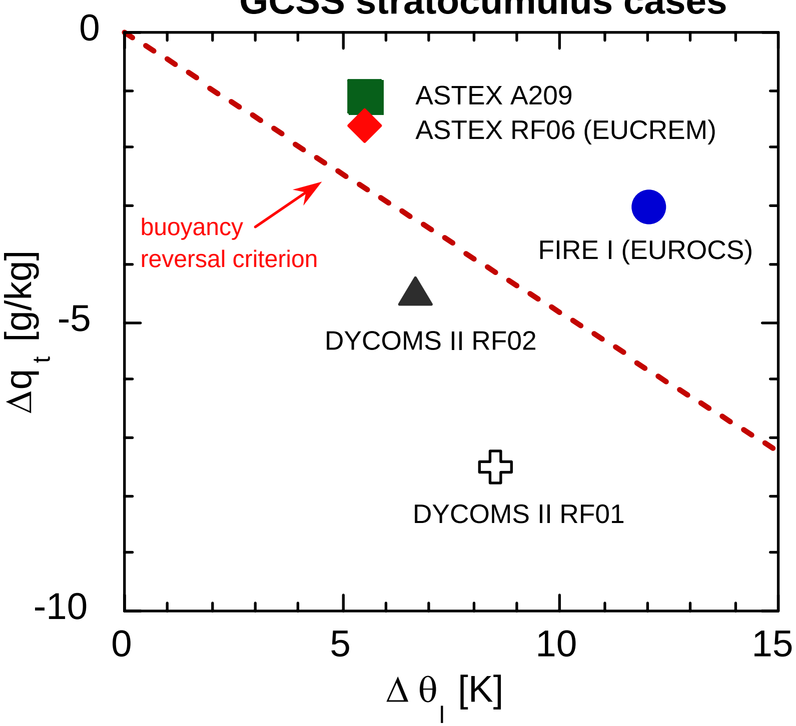
$$w_e = \frac{2A_{AL}W_{NE} + \alpha_t A_W \Delta F_L/\left(\rho c_p\right)}{\Delta\theta_v}$$

- Moeng (2000)

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

# Stratocumulus : Top-entrainment Observations vs Parameterizations

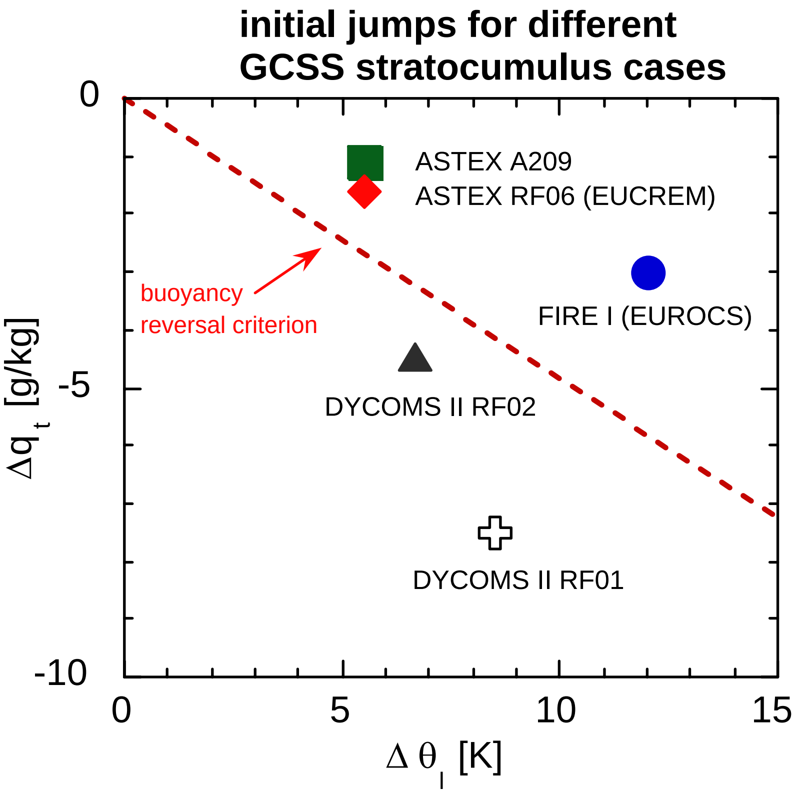
**initial jumps for different GCSS stratocumulus cases**




**Entrainment results (cm/s) of 4 GCSS Cases**

| | FIRE | DYCOMS RF01 | ASTEX A209 | ASTEX RF06 |
|---|---|---|---|---|
| Observed | - | | 1.1±0.5 | 1.2 ±1 |
| LES | 0.58 ± 0.08 | | 1.2 ± 0.3 | 1.9 ± 0.1 |
| NT | 0.38 | | 1.21 | 1.86 |
| Lock | 0.19 | | 0.85 | 1.13 |
| SB | 0.38 | | 0.76 | 1.18 |
| Moeng | 0.57 | | 1.35 | 1.53 |
| Lilly | 0.37 | | 0.99 | 1.42 |

# Stratocumulus : Top-entrainment Observations vs Parameterizations

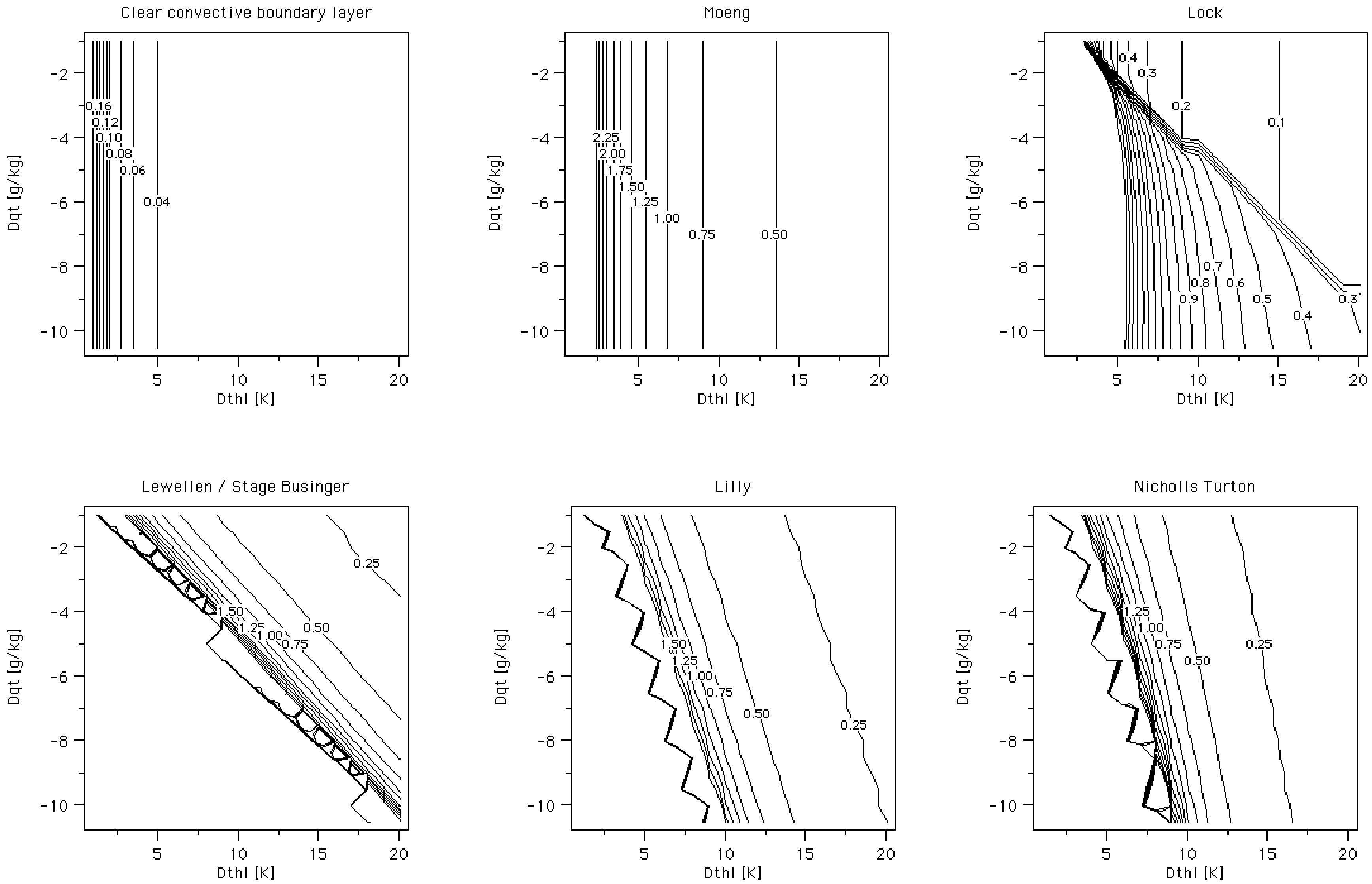



**Entrainment results (cm/s) of 4 GCSS Cases**

| | FIRE | DYCOMS RF01 | ASTEX A209 | ASTEX RF06 |
|---|---|---|---|---|
| Observed | - | 0.38 ± 0.1 | 1.1±0.5 | 1.2 ±1 |
| LES | 0.58 ± 0.08 | 0.50 ± 0.09 | 1.2 ± 0.3 | 1.9 ± 0.1 |
| NT | 0.38 | 0.72 | 1.21 | 1.86 |
| Lock | 0.19 | 0.33 | 0.85 | 1.13 |
| SB | 0.38 | 0.88 | 0.76 | 1.18 |
| Moeng | 0.57 | 0.69 | 1.35 | 1.53 |
| Lilly | 0.37 | 0.78 | 0.99 | 1.42 |

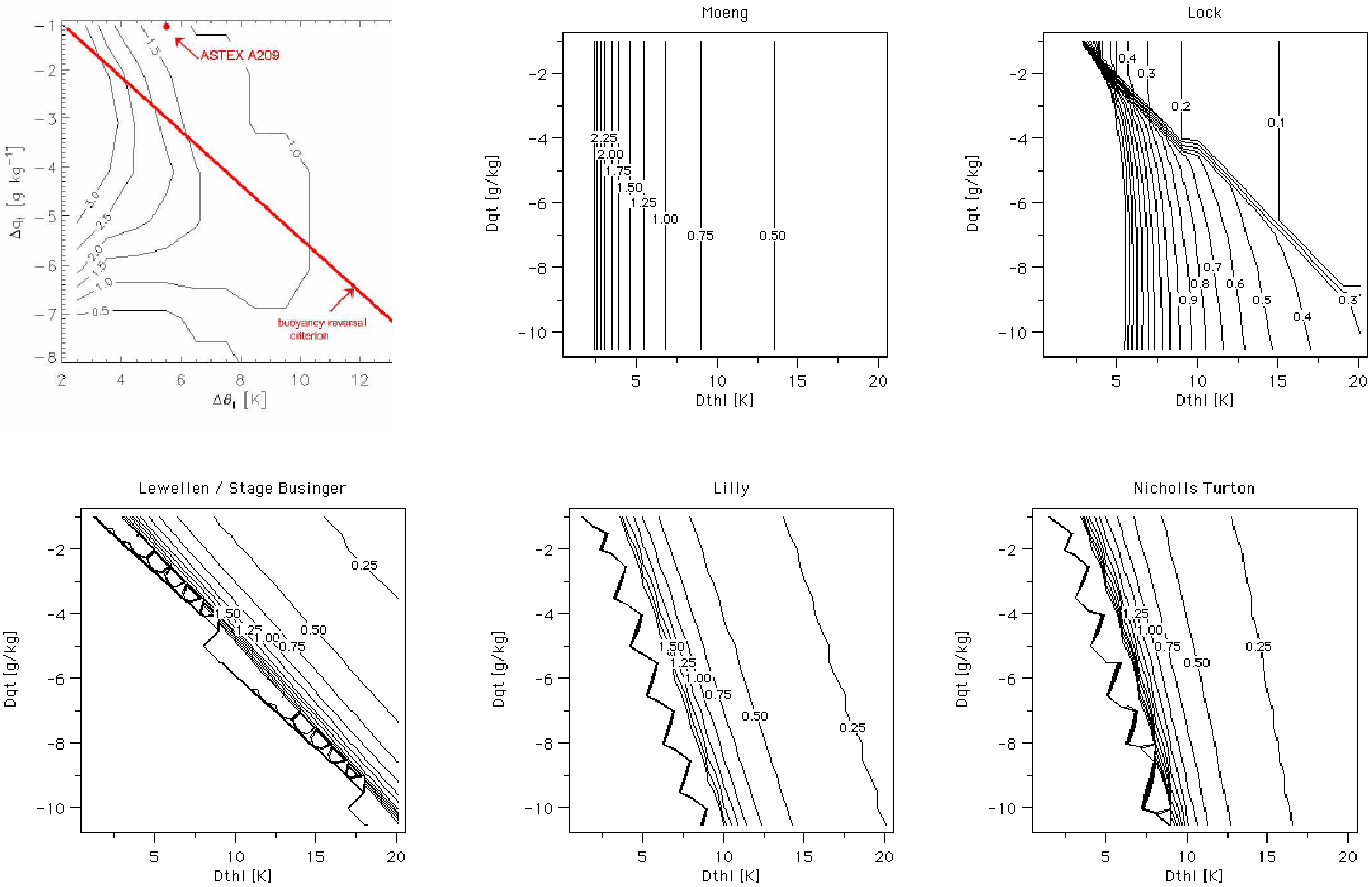
# Entrainment rates for ASTEX by varying jumps at the top of Scu

## (De Roode, Lenderink and Koehler, to be submitted)



# Comparison of TKE-scheme with we-parameterizations

## (De Roode, Lenderink and Koehler, to be submitted)



# Conclusions (part 1)

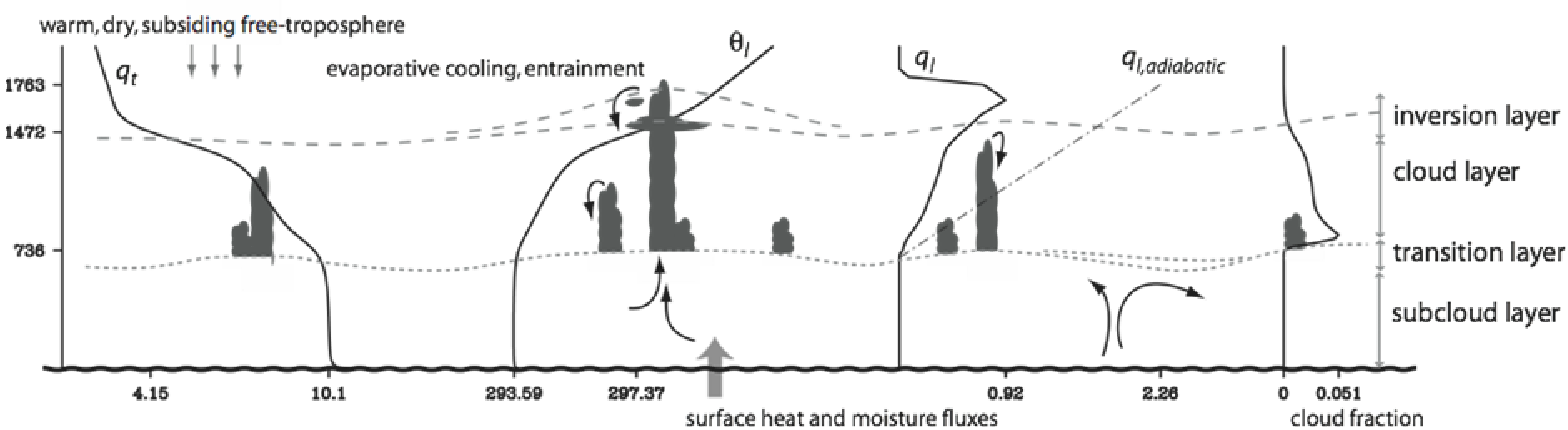
•Mixing in Scu should be done in moist conserved variables

•Key problem is (still) the correct parameterization of the top-entrainment

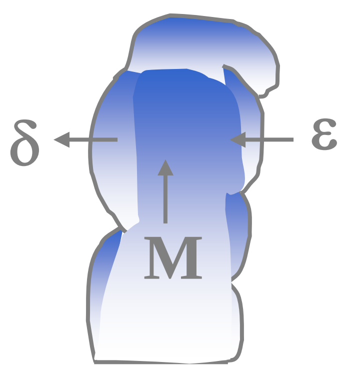
•Recent Field experiments (i.e. DYCOMS) do impose strong(er) constraints on top-entrainment and form critical tests for parameterizations  LES data

•For higher(vertical) resolution (dz~100m), TKE-schemes without explicit top-entrainment seem to be an acceptable alternative for parameterizations with explicit top-entrainment parameterizations.

# Shallow Cumulus: Characteristics




Convective Transport in Shallow Cu usually parameterized using the **mass flux approach**:




$$\partial_t \phi|_{\text{clouds}} = -\partial_z F^{\phi}$$

$$F^{\phi} = \frac{M}{\rho}(\phi^c - \phi).$$

$$\begin{aligned} \partial_z M &= (\epsilon - \delta) M \\ \partial_z \phi^c &= -\epsilon(\phi^c - \phi). \end{aligned}$$

# Shallow Cumulus: Lateral entrainment rate ε


Siebesma and Cuypers JAS 95

Siebesma 1998

Grant and Brown QJRMS 1999

Gregory QJRMS 2000

Neggers et al JAS 2002


- Active topic of research over the last 10 years.
- Due to the fact that it is possible to obtain reliable estimates for ε from both observation and LES.

## Main Results:

1. Lateral entrainment and detrainment rates typically of the order of $10^{-3}$ $m^{-1}$
2. Detrainment rates typically larger than entrainment rates or
3. Mass flux decreases with height

$$\frac{\partial \ln M}{\partial z} = \varepsilon - \delta$$

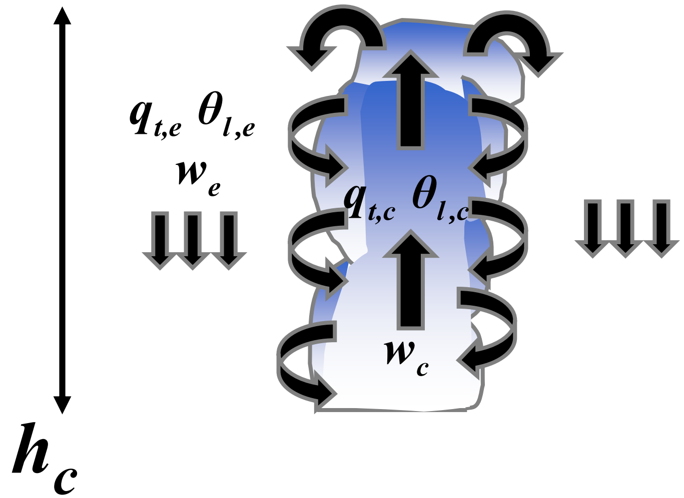
## Heuristic Argument:

$$for\ \phi \in \{\theta_l , q_t\}:$$

$$\frac{d\phi_c}{dt} = F_{mixing}$$

$$w_c \frac{\partial \phi_c}{\partial z} = -\frac{(\phi_c - \phi_e)}{\tau}$$

$$\frac{\partial \phi_c}{\partial z} = -\varepsilon(\phi_c - \phi_e) \quad \text{where} \quad \varepsilon = \frac{1}{w_c \tau} \approx \frac{1}{h_c} \quad \rightarrow \varepsilon \cong cz^{-1}$$



# Shallow Cumulus: Lateral Detrainment Rates

- Detrainment has received less attention than entrainment.
- Varies much more from case to case so is probably more important to parameterize mass flux correctly

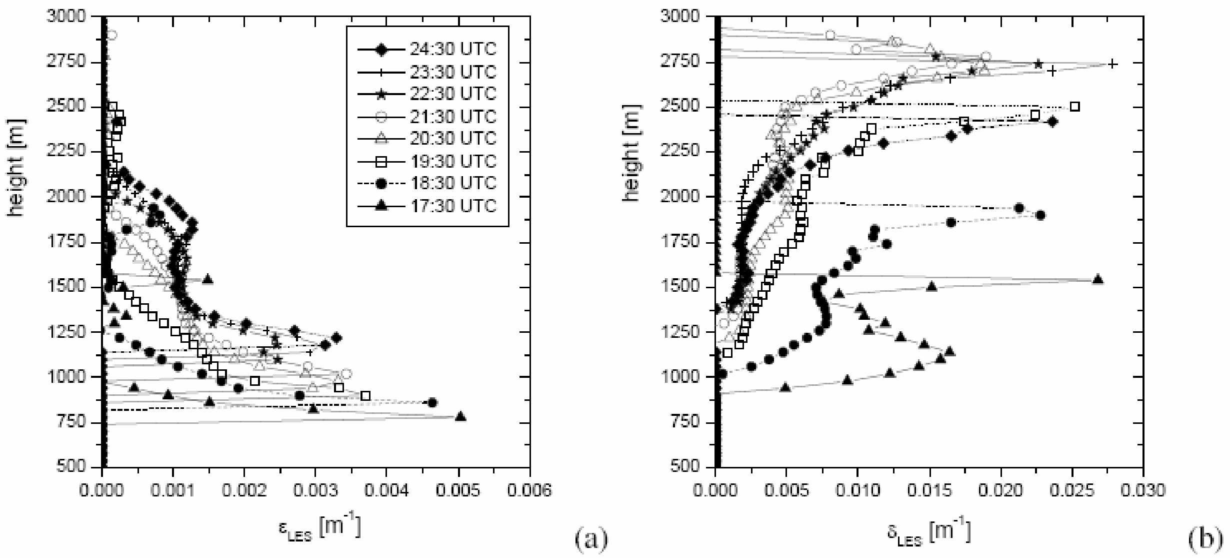
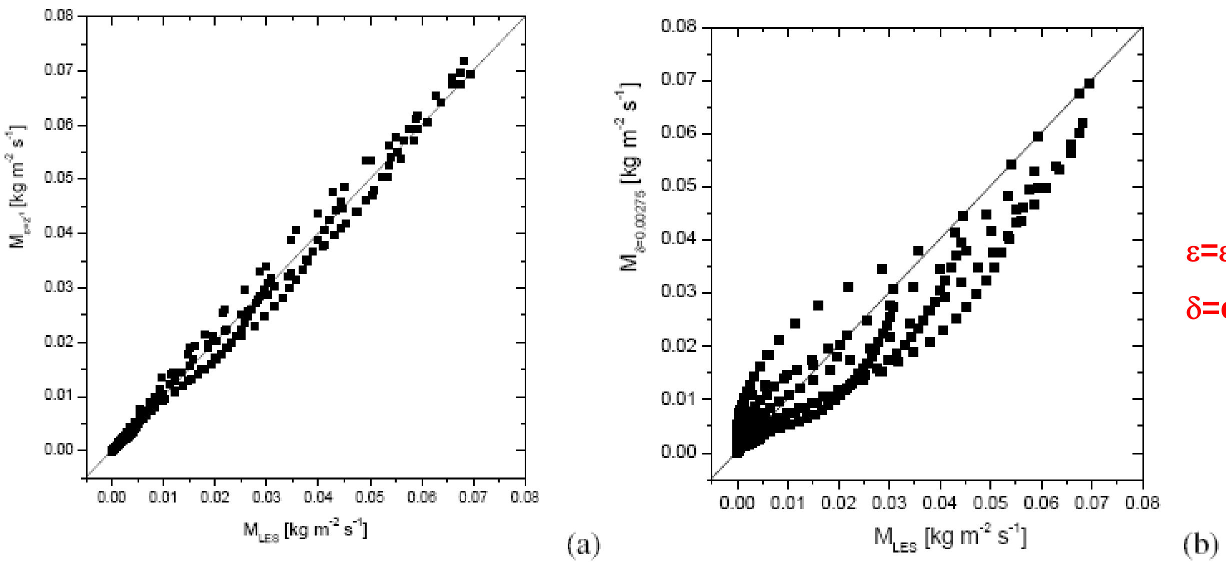



FIGURE 3: Hourly averaged fractional entrainment (a) and detrainment (b) rates diagnosed from LES results for the ARM case. Note the different x-axis scale for (a) and (b).

# Shallow Cumulus: Lateral Detrainment Rates

$\varepsilon = 1/z$

$\delta = \delta$_LES




$$\frac{\partial \ln M}{\partial z} = \varepsilon - \delta$$

$\varepsilon = \varepsilon$_LES

$\delta$=constant

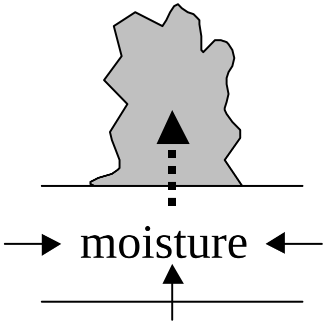
FIGURE 4: Comparison of the Mass flux for the ARM case as directly diagnosed from LES with (a) the mass flux obtained using a fixed parameterized fractional entrainment rate ($\varepsilon = z^{-1}$) along with the dynamical LES diagnosed $\delta$ or (b) with the mass flux obtained using a fixed parameterized fractional detrainment rate ($\delta = 2.75 \times 10^{-3}$) along with the dynamical LES diagnosed $\varepsilon$.

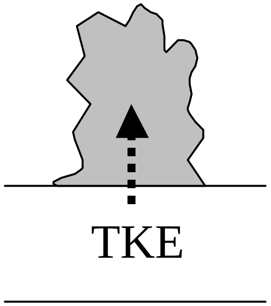
- **A simple entrainment parameterization : $\varepsilon \sim 1/z$ is sufficient**
- **A constant detrainment rate is inappropriate**
- **For a new simple dynamical parameterization of detrainment : de Rooy&Siebesma 2007, submitted to MWR.**

# Shallow Cumulus: Cloudbase Mass Flux (Closure)

**Neggers et al 2004 MWR**

**Coupling of $M_b$ to *sub-cloud* layer**



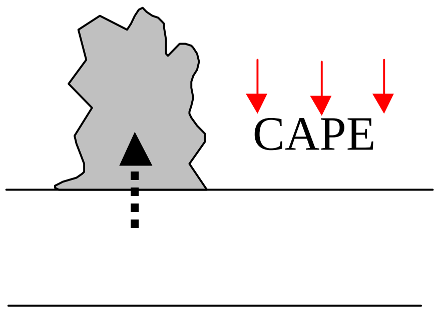




$$M_b^{\,c} = \gamma \;\; a_b^{\,c} \;\; w^*_{sub} \approx 0.03 w^*_{sub}$$

**Grant 2001 QRMS**

**OR:**

**Coupling of $M_b$ to *cloud* layer**




**Detailed comparisons of SCM with LES indicate that shallow cu is driven by the subcloud layer and that a TKE-type of closure is a superior closure.**

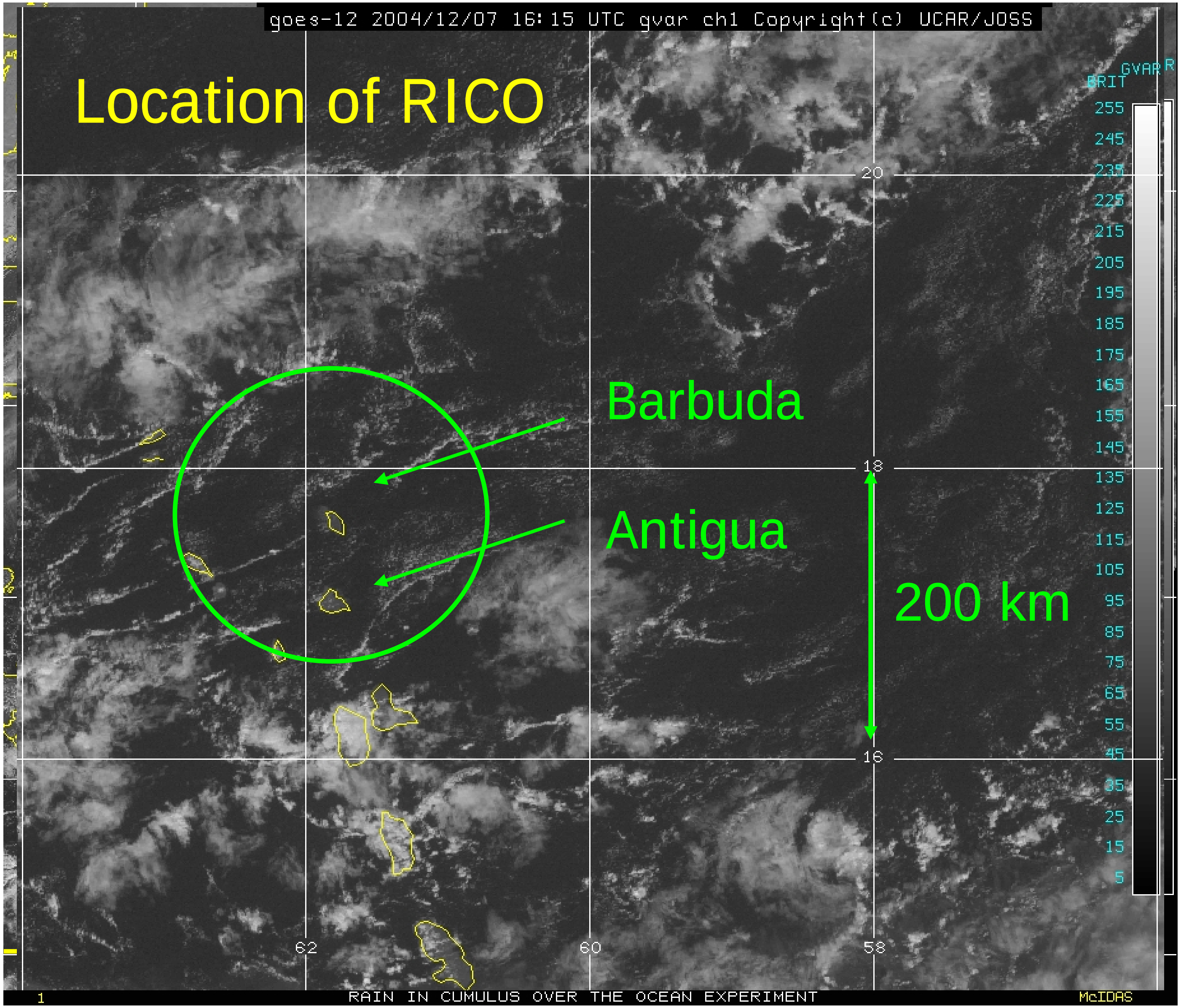
## How about precipitation in Shallow Cumulus?

Latest GCSS Boundary Layer Clouds Working Group (GCSS-BLCWG) Intercomparison case is based on Precipitating shallow cumulus such as observed during


"To understand shallow cumulus and processes involved at all relevant scales, with special attention to precipitation "

**Information:** www.knmi.nl/samenw/rico

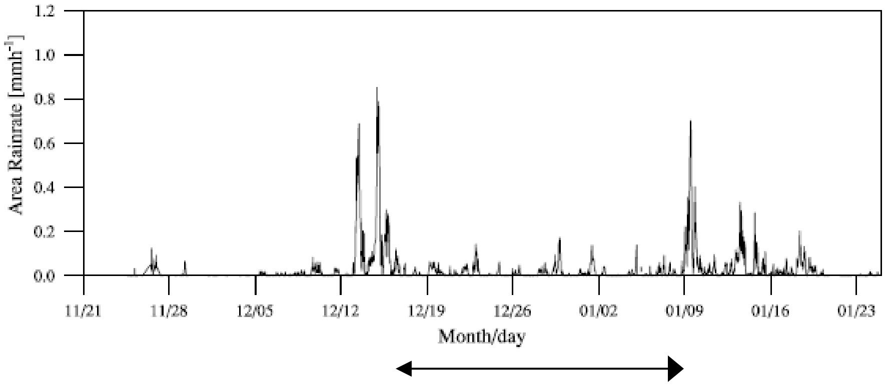
# The RICO field study (B. Rauber, L. di Girolamo, H. Gerber, L. Nuijens, B. Stevens



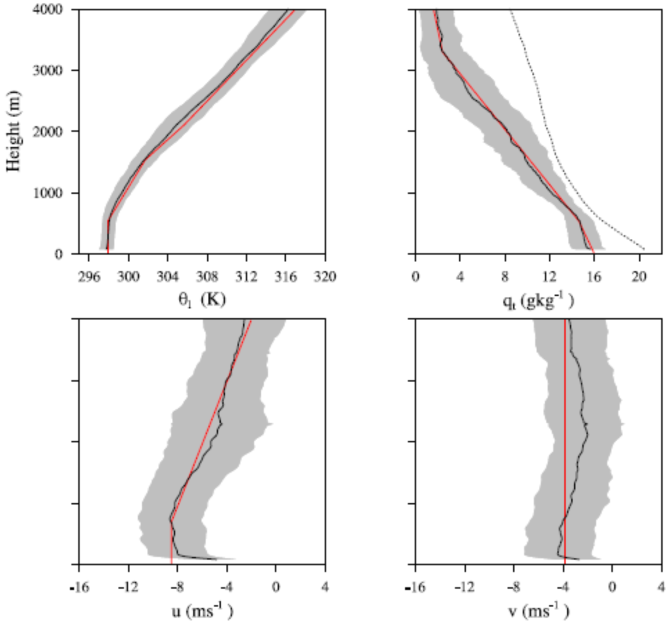
# Modelling Strategy:

## Construct a composite based on a suppressed period

## from 16/12/04 till 08/01/05




**Average precip in this period: ~0.34 mm/day**

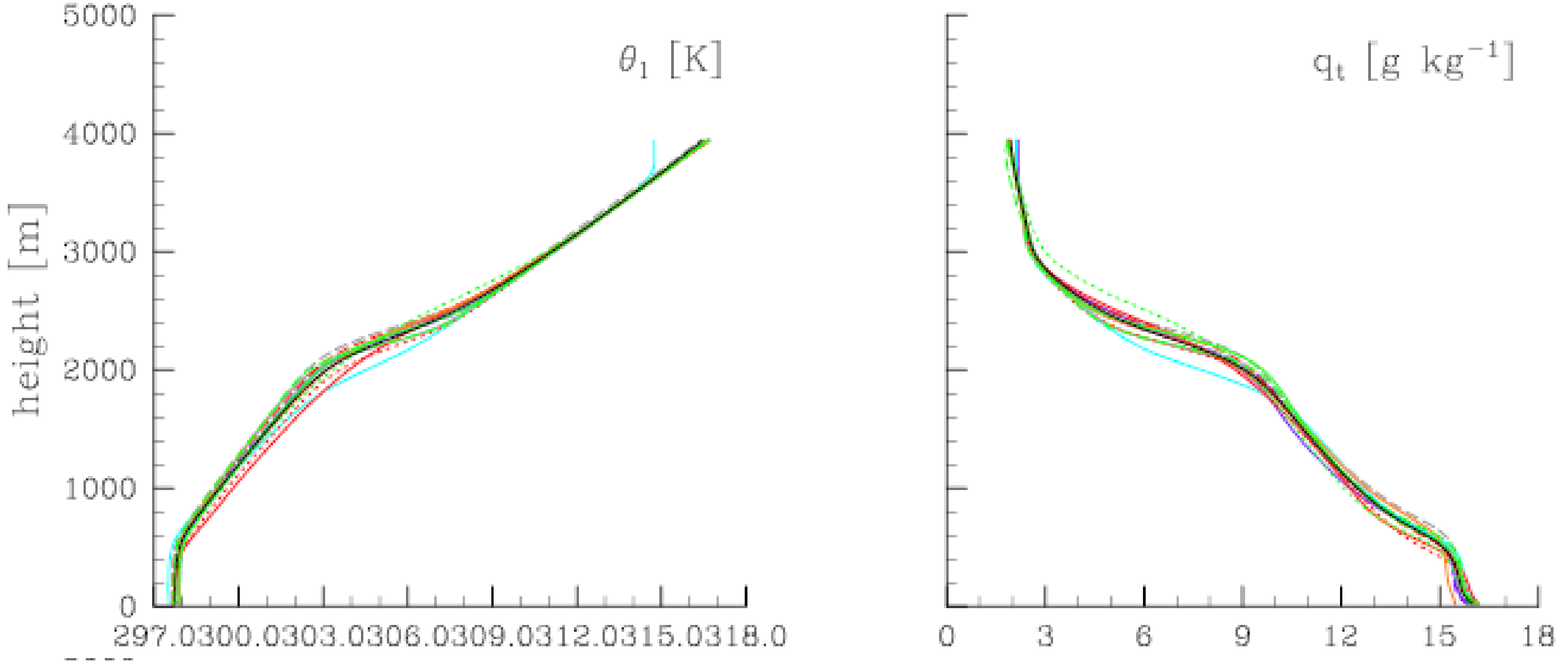



**Average Soundings for this period**

### Main critical test

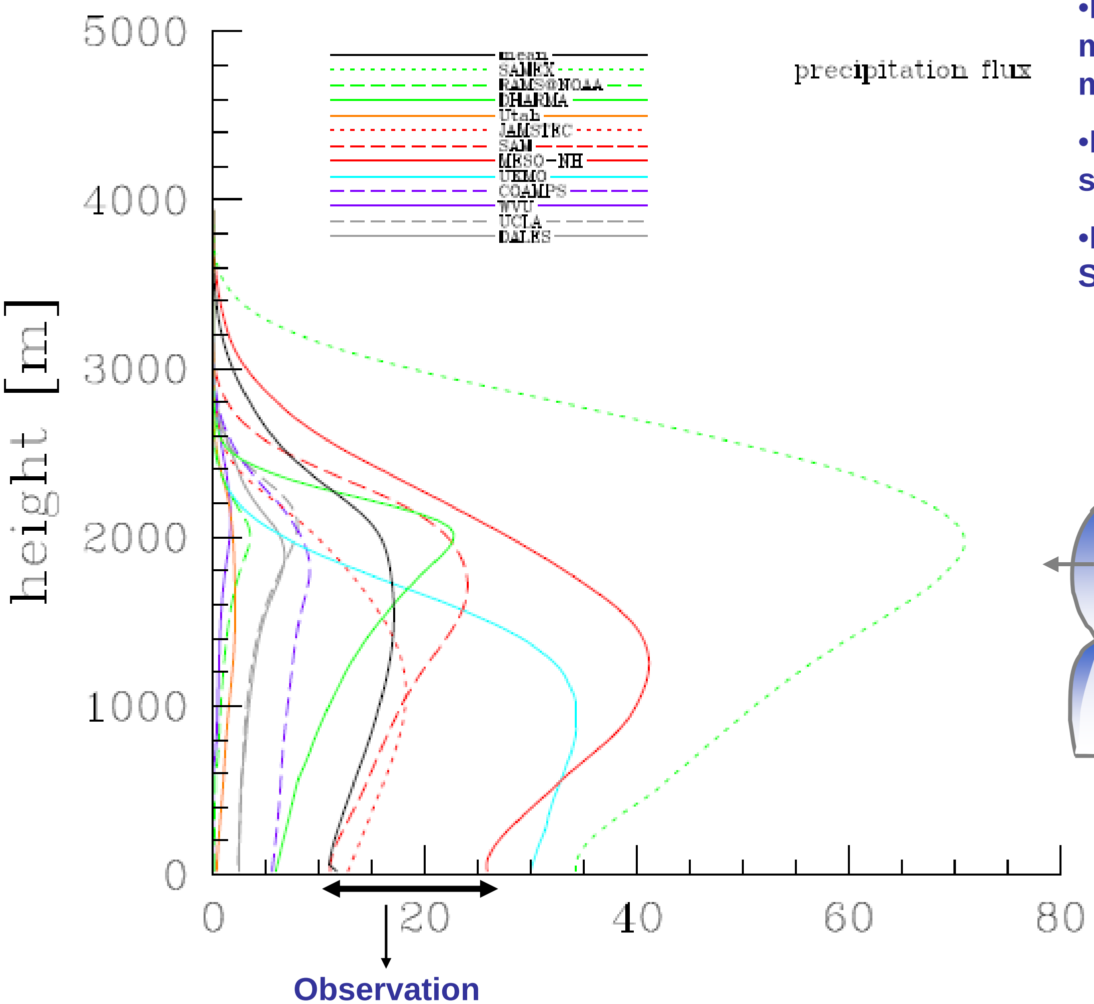
**Are the LES models and the SCM-versions of GCM's, 'LAM's and mesoscale models capable of representing realistic mean state when subjected to the best guess of the applied large scale forcings.**

# Mean Profiles of LES after 24 hours

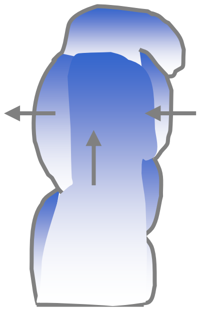


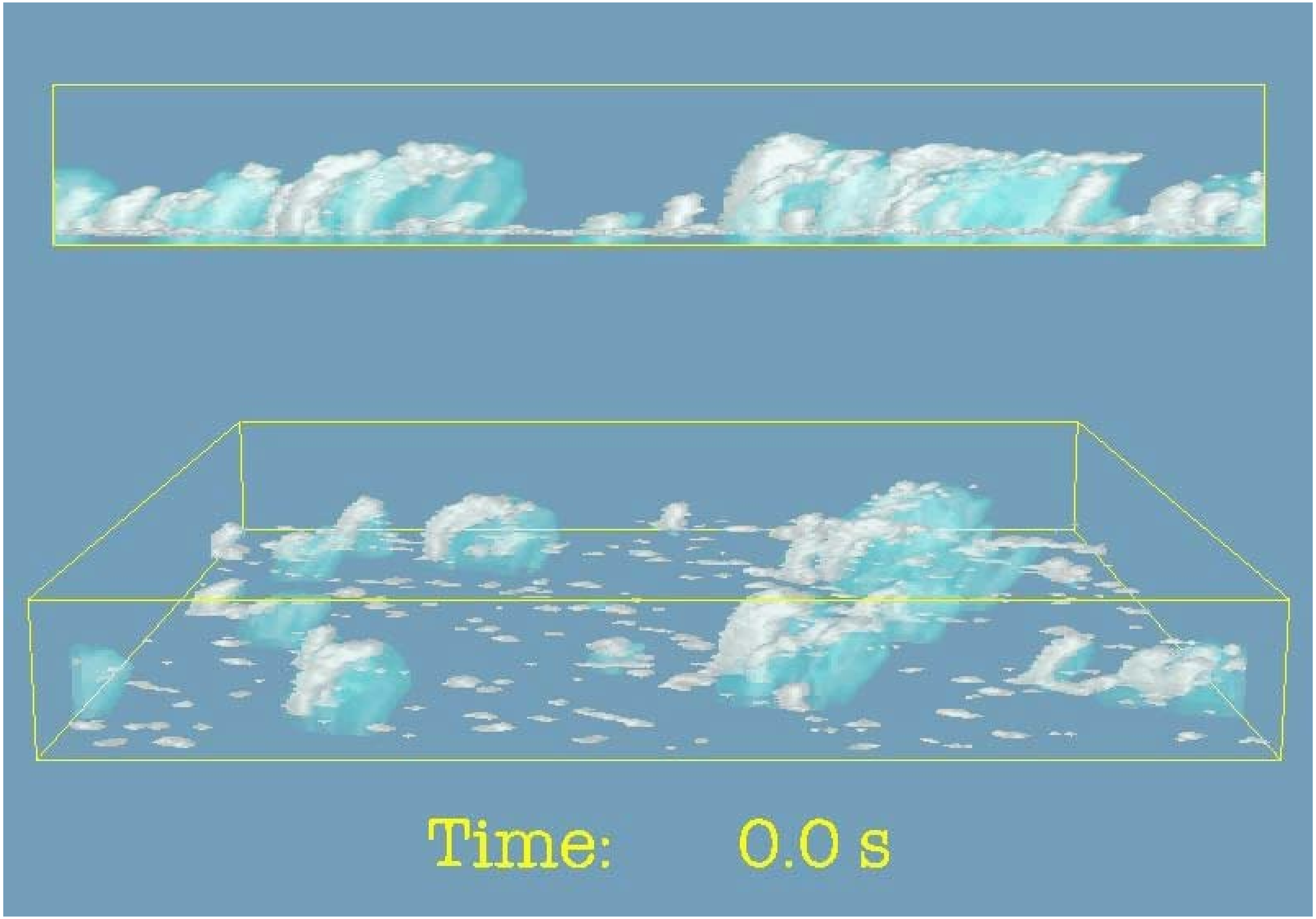

**Reasonable agreement on the mean state for participating LES models**

# Precipitation Fluxes LES after 24 hours




- Large Spread in precipitation (especially between models that use (sophisticated) explicit bin-microphysics.
- Differences not yet tied to choice of microphysical scheme
- Precipitation flux peaks near cloud top (contrary to Scu). Evaporation of rain is a important process.





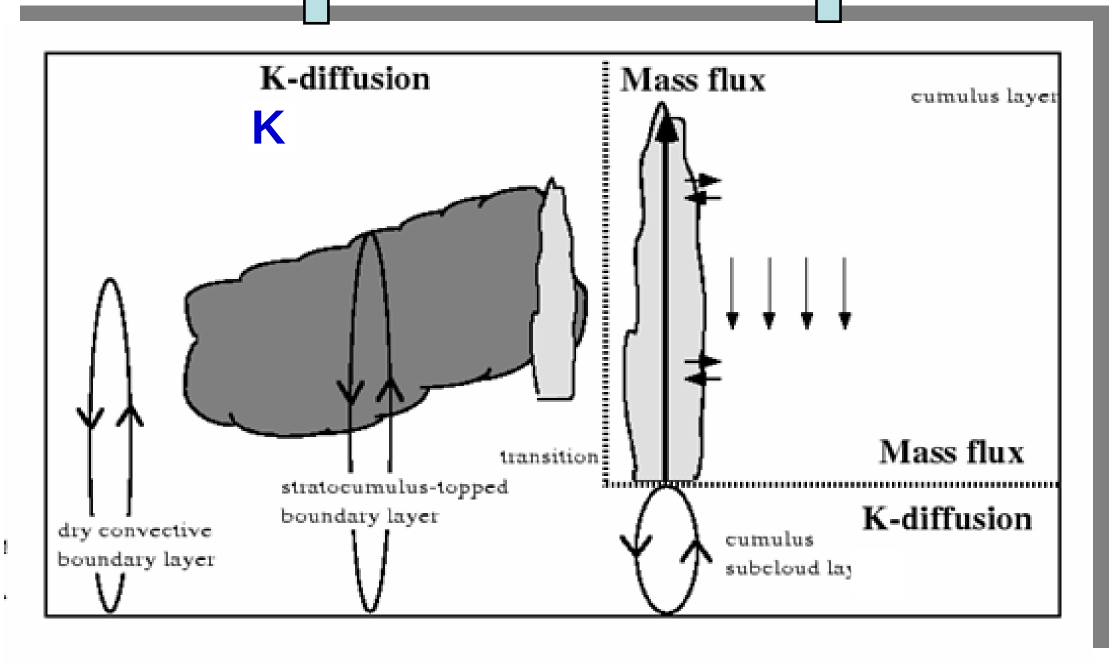

Courtesy : Steve Abel (Met Office)

# So far this was a schizofrenic presentation

*Different Parameterization approaches for Scu and shallow Cu developed by different communities.*

$$\overline{w'\phi'} \cong -K \frac{\partial \overline{\phi}}{\partial z}$$

$$\overline{w'\phi'} \cong M(\phi_u - \overline{\phi})$$




$$\frac{\partial \overline{\phi}}{\partial t} \cong -\frac{\partial}{\partial z}\left(\overline{w'\phi'}\right) + \overline{S}$$

*This unwanted situation has led to:*

- ***Double counting of processes***
- ***Interface problems***
- ***Problems with transitions between different regimes***

**This sad state of affairs calls for a more unified approach of the cloudy PBL!!**

# OPTIONS

**“Regime Thinking” :** **Try to find good criteria to diagnose Scu or Cu and treat  those regimes seperately (Met Office Model)**

**“Unified Approach” :** **Try to couple the diffusion and and “ädvective” mass flux approach in a physical sound way.**

**see presentations of: Cara-Lyn Lappen,  Martin Koehler and Julien Pergaud.**

Further reading: Siebesma and Texeira AMS proceedings 2000

Lappen and Randall: JAS 2001

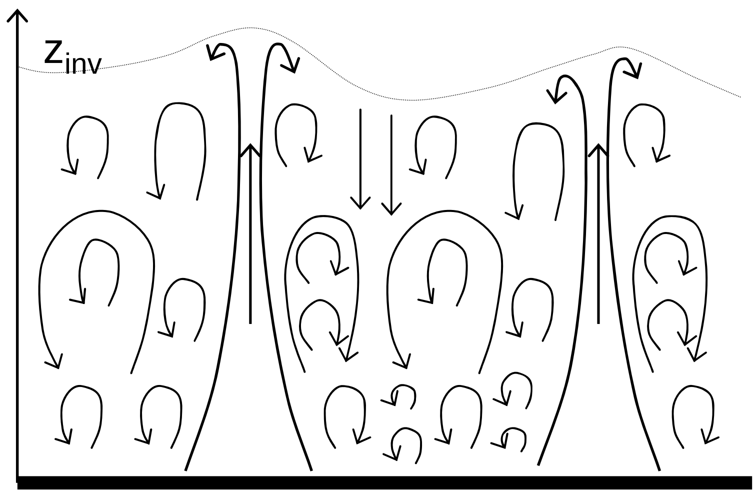
Soares et al QJRMS 2004

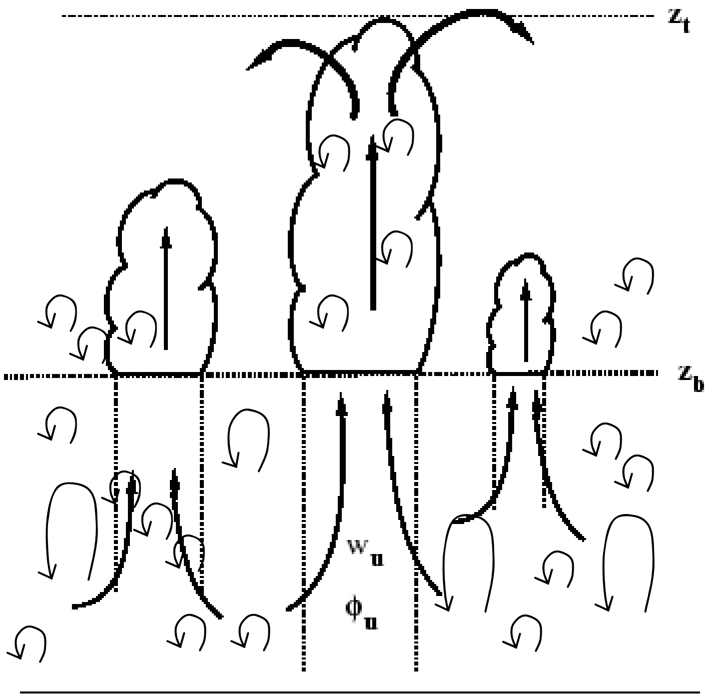
Siebesma et al. To appear in March 2007 JAS

# The Idea :

- **Nonlocal (Skewed) transport through strong updrafts in clear and cloudy boundary layer by advective Mass Flux (MF) approach**

- **Remaining (Gaussian) transport done by an Eddy Diffusivity (ED) approach**

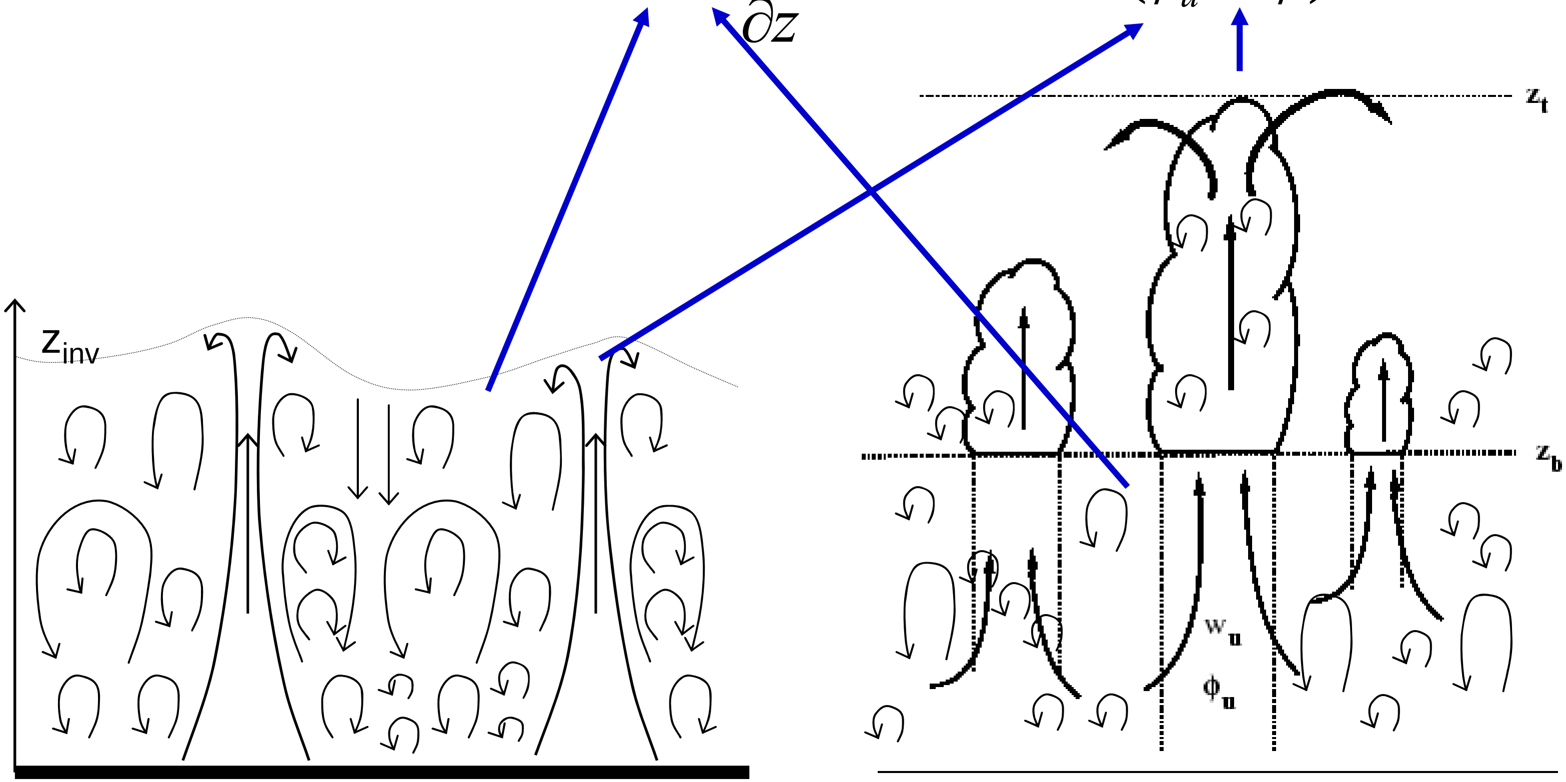


# The (simplest) Mathematical Framework :

$$\overline{w'\phi'} = a_u \overline{w'\phi'}^u + (1-a_u)\overline{w'\phi'}^e + a_u w_u (\phi_u - \phi_e)$$

$$\cong \quad -K\frac{\partial\overline{\phi}}{\partial z} + \quad M(\phi_u - \overline{\phi})$$



# Conclusions (Shallow Cu)

**There has been a considerable increase in our understanding of shallow cu:**

1. Shallow cu is driven by the subcloud layer
2. Mass flux concept is a sound approach for parameterizing
3. We know how to parametrize the lateral entrainment process
4. A smart combination of mass flux and K-diffusion easies
    1. The triggering problem
    2. the diurnal cycle (transition clear->cloudy and vice-versa)

**But….more attention is needed for**

1. The detrainment process
2. The incloud vertical velocity equation
3. the precipitation process
4. Momentum transport