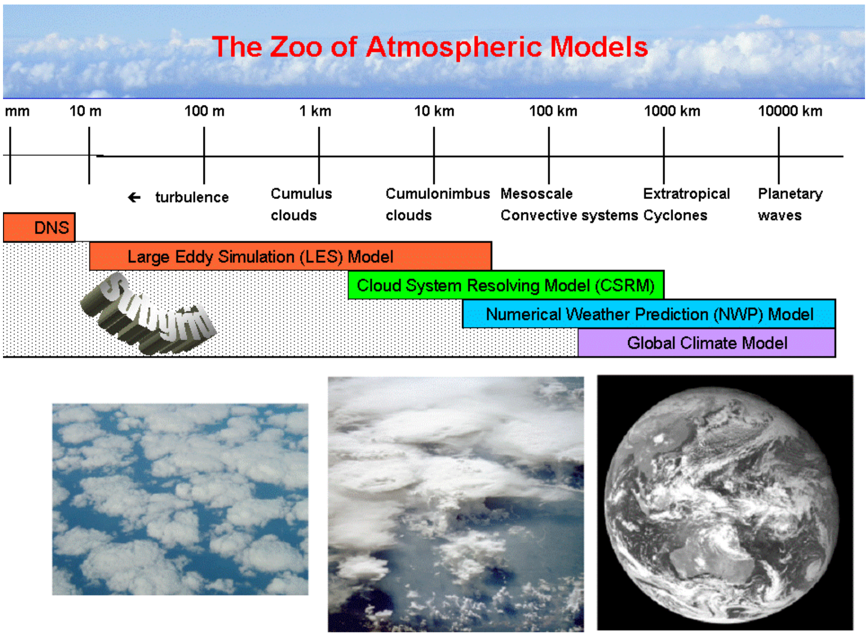
Parametrization of boundary layer clouds: A GCSS perspective

Pier Siebesma

KNMI, De Bilt, The Netherlands
and Technical University Delft, Multiscale Physics Group, Delft, The Netherlands
Email: siebesma@knmi.nl

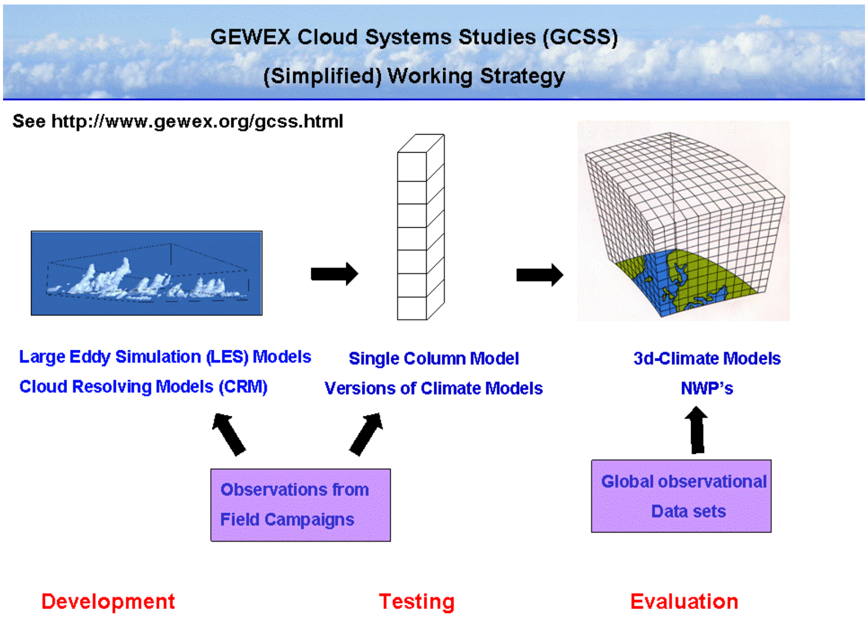


The Zoo of Atmospheric Models

mm | 10 m | 100 m | 1 km | 10 km | 100 km | 1000 km | 10000 km

← turbulence | Cumulus clouds | Cumulonimbus clouds | Mesoscale Convective systems | Extratropical Cyclones | Planetary waves

DNS
Large Eddy Simulation (LES) Model
Cloud System Resolving Model (CSRM)
Numerical Weather Prediction (NWP) Model
Global Climate Model



GEWEX Cloud Systems Studies (GCSS)
(Simplified) Working Strategy

See http://www.gewex.org/gcss.html

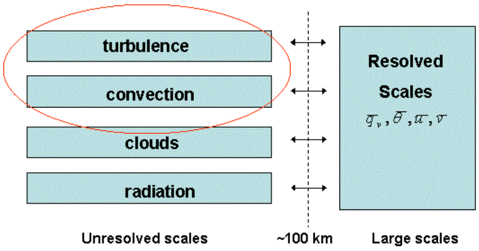
Large Eddy Simulation (LES) Models
Cloud Resolving Models (CRM)
→
Single Column Model
Versions of Climate Models
→
3d-Climate Models
NWP's

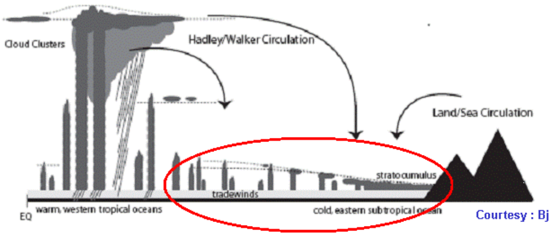
Observations from Field Campaigns

Global observational Data sets

Development | Testing | Evaluation

History and Progress in Convential Parameterizations for the Cloudy PBL





Courtesy : Bjorn Stevens

Grid Averaged Equations of thermodynamic variables

$$\frac{\partial \overline{\theta}}{\partial t} = -\overline{\mathbf{v}}\cdot\nabla\overline{\theta} - \overline{w}\frac{\partial \overline{\theta}}{\partial z} - \frac{\partial}{\partial x_i}\overline{u_i'\theta'} + \frac{L}{\pi c_p}(c-e) + Q_{rad}$$

$$\frac{\partial \overline{q}_v}{\partial t} = -\overline{\mathbf{v}}\cdot\nabla\overline{q}_v - \overline{w}\frac{\partial \overline{q}_v}{\partial z} - \frac{\partial}{\partial x_i}\overline{u_i'q_v'} - (c-e)$$

$$\frac{\partial \overline{q}_l}{\partial t} = -\overline{\mathbf{v}}\cdot\nabla\overline{q}_l - \overline{w}\frac{\partial \overline{q}_l}{\partial z} - \frac{\partial}{\partial x_i}\overline{u_i'q_l'} + (c-e) - P_r$$

Large scale advection

Large scale subsidence

turbulent transport

Net Condensation Rate

Introduce moist conserved variables!

$$\theta_l \approx \theta - \frac{L}{c_p\pi}q_l$$

•Liquid water potential Temperature

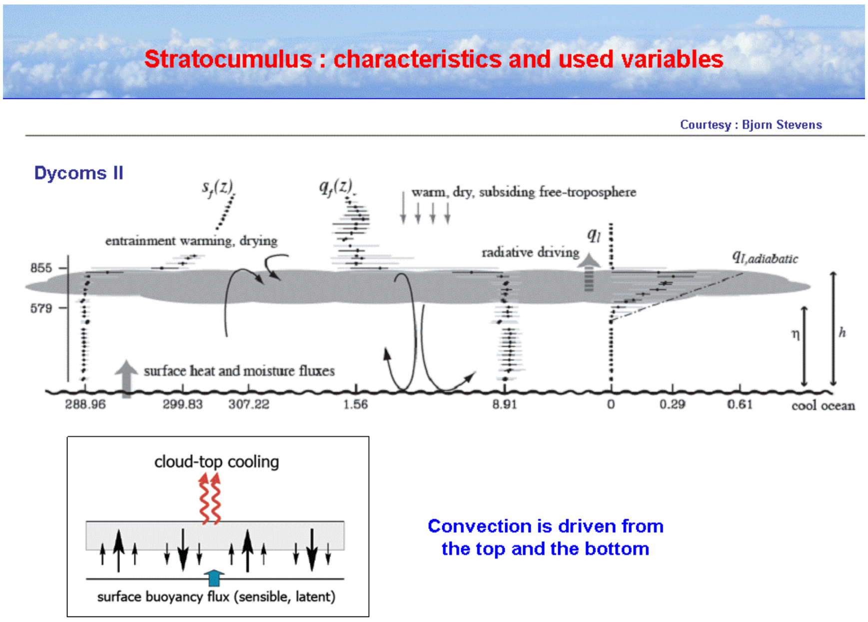
$$q_t \equiv q_v + q_l$$

•Total water specific humidity

$$\frac{\partial \overline{\theta}_l}{\partial t} = -\overline{\mathbf{v}}\cdot\nabla\overline{\theta}_l - \overline{w}\frac{\partial \overline{\theta}_l}{\partial z} - \frac{\partial}{\partial z}\overline{w'\theta_l'} + Q_{rad}$$

$$\frac{\partial \overline{q}_t}{\partial t} = -\overline{\mathbf{v}}\cdot\nabla\overline{q}_t - \overline{w}\frac{\partial \overline{q}_t}{\partial z} - \frac{\partial}{\partial z}\overline{w'q_t'} - P_r$$

Parameterization issue reduced to finding the subgrid fluxes

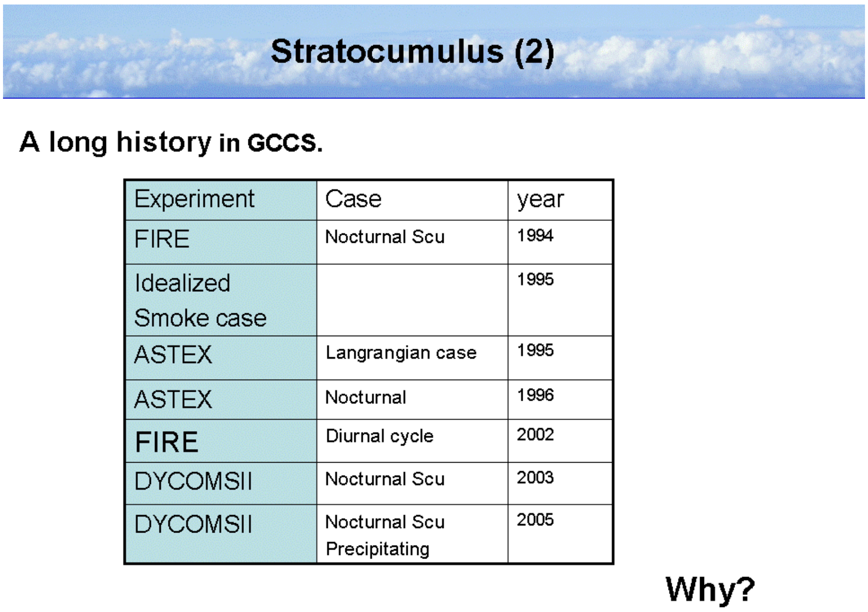


Stratocumulus : characteristics and used variables

Courtesy : Bjorn Stevens

Dycoms II

Convection is driven from the top and the bottom

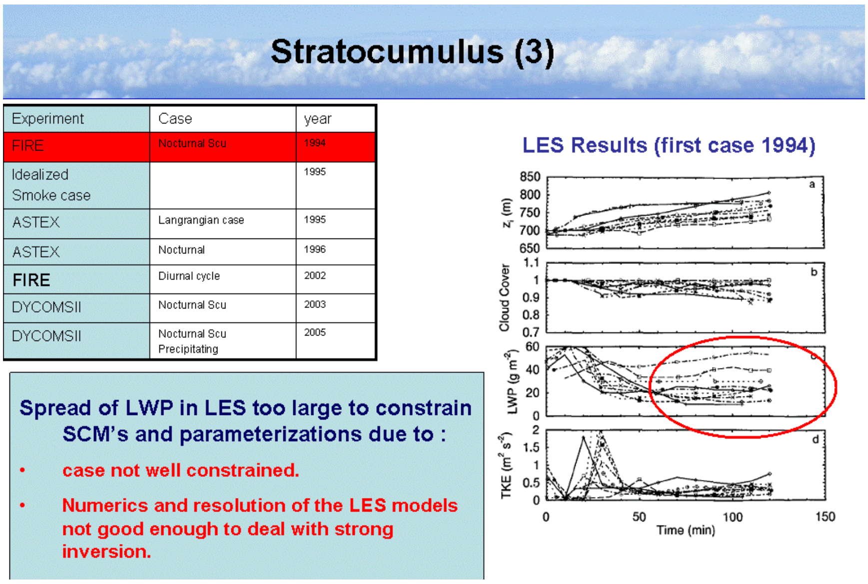


Stratocumulus (2)

A long history in GCCS.

Experiment	Case	year
FIRE	Nocturnal Scu	1994
Idealized Smoke case		1995
ASTEX	Langrangian case	1995
ASTEX	Nocturnal	1996
FIRE	Diurnal cycle	2002
DYCOMSII	Nocturnal Scu	2003
DYCOMSII	Nocturnal Scu Precipitating	2005

Why?



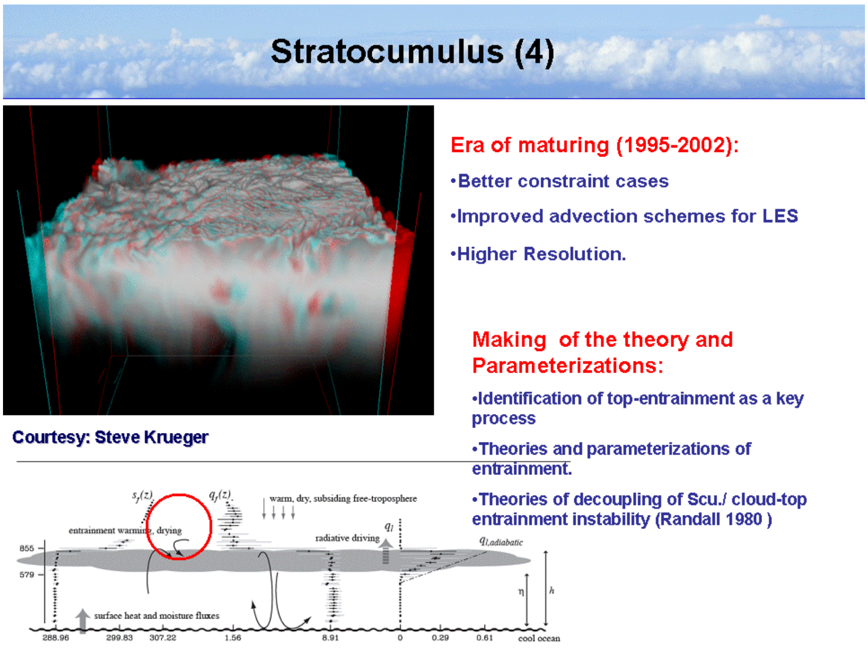
Stratocumulus (3)

Experiment	Case	year
FIRE	Nocturnal Scu	1994
Idealized Smoke case		1995
ASTEX	Langrangian case	1995
ASTEX	Nocturnal	1996
FIRE	Diurnal cycle	2002
DYCOMSII	Nocturnal Scu	2003
DYCOMSII	Nocturnal Scu Precipitating	2005

Spread of LWP in LES too large to constrain SCM's and parameterizations due to :

- case not well constrained.
- Numerics and resolution of the LES models not good enough to deal with strong inversion.

LES Results (first case 1994)



Stratocumulus (4)

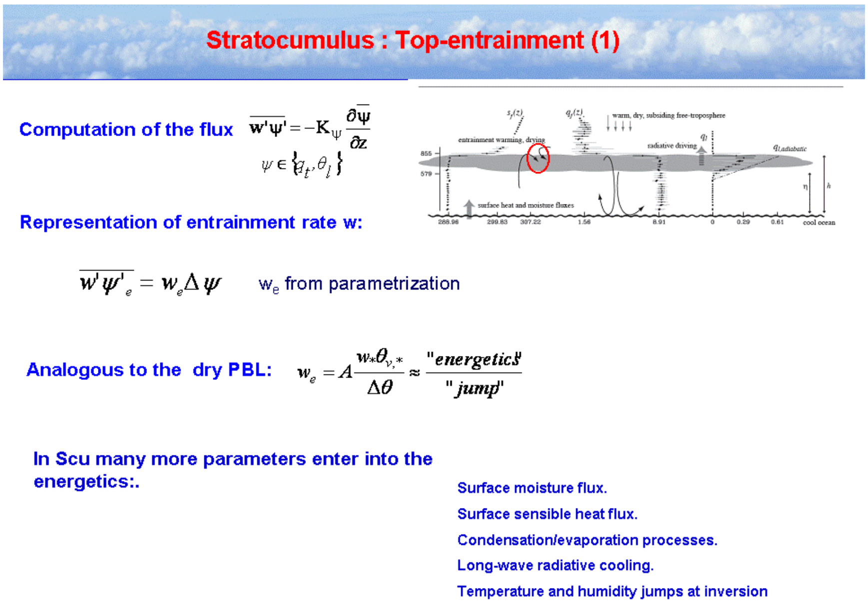
Courtesy: Steve Krueger

Era of maturing (1995-2002):

- Better constraint cases
- Improved advection schemes for LES
- Higher Resolution.

Making of the theory and Parameterizations:

- Identification of top-entrainment as a key process
- Theories and parameterizations of entrainment.
- Theories of decoupling of Scu./ cloud-top entrainment instability (Randall 1980)



Stratocumulus : Top-entrainment (1)

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

$\psi \in \{q_t, \theta_l\}$

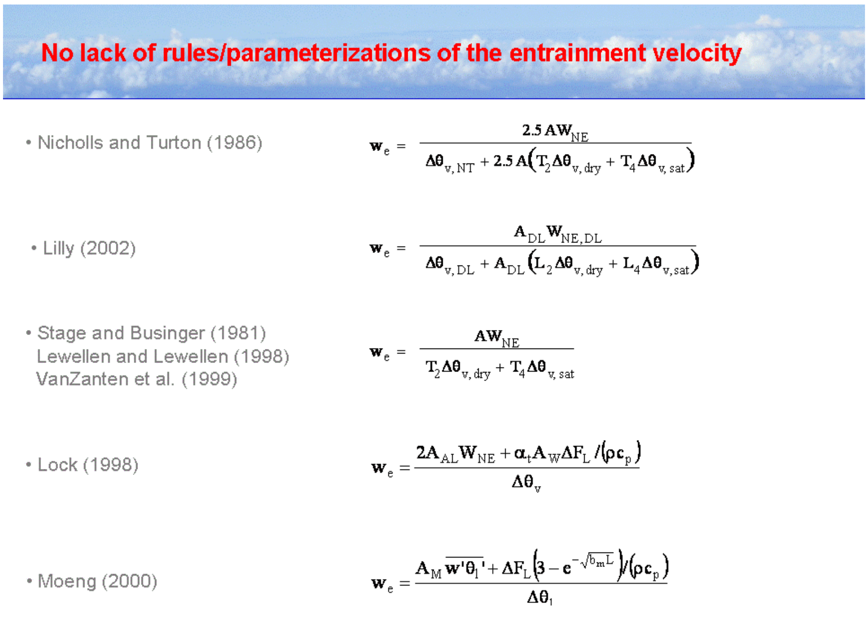
Representation of entrainment rate w:

$\overline{w'\psi'}_e = w_e \Delta\psi$ w_e from parametrization

Analogous to the dry PBL: $w_e = A\frac{w_* \theta_{v,*}}{\Delta\theta} \approx \frac{\text{"}energetics\text{"}}{\text{"}jump\text{"}}$

In Scu many more parameters enter into the energetics:.

Surface moisture flux.
Surface sensible heat flux.
Condensation/evaporation processes.
Long-wave radiative cooling.
Temperature and humidity jumps at inversion



No lack of rules/parameterizations of the entrainment velocity

- Nicholls and Turton (1986)

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

- 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)

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

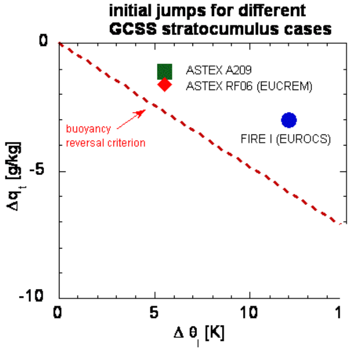
- Lock (1998)

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

- Moeng (2000)

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

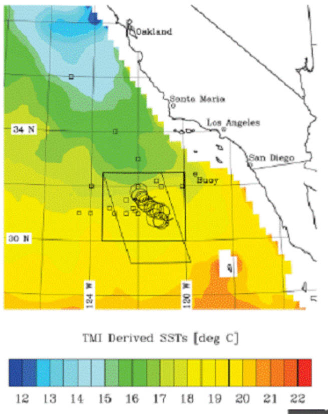
Stratocumulus : Entrainment velocities: Observations vs Parameterizations



Entrainment velocities (cm/s) of 3 GCSS Cases

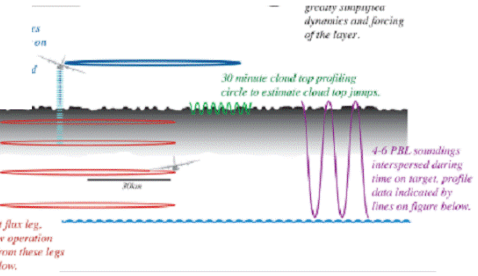
	FIRE	ASTEX A209	ASTEX RF06
Observed	-	1.1±0.5	1.2 ±1
LES	0.58 ± 0.08	1.2 ± 0.3	1.9 ± 0.1
NT	0.38	1.21	1.86
Lock	0.19	0.85	1.13
SB	0.38	0.76	1.18
Moeng	0.57	1.35	1.53
Lilly	0.37	0.99	1.42

Uncertainty in entrainment rate has inspired the GCSS-community to design a special dedicated field experiment to narrow down the uncertainty of this key process

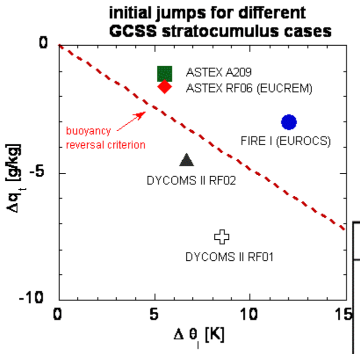


DYCOMS II

B. Stevens et al. BAMS 84 (2003)

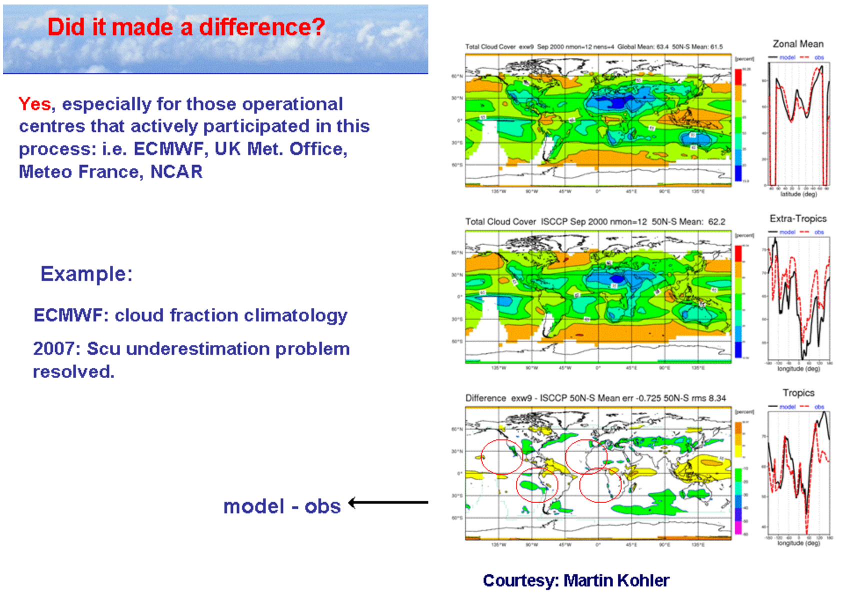


Incorporating DYCOMS results: narrowing down parametrizations!



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



Did it made a difference?

Yes, especially for those operational centres that actively participated in this process: i.e. ECMWF, UK Met. Office, Meteo France, NCAR

Example:

ECMWF: cloud fraction climatology

2007: Scu underestimation problem resolved.

model - obs

Courtesy: Martin Kohler

Lessons to be learned!!

- use observations and models to identify the weak spots (top-entrainment)
- advance theories to improve representation (entrainment closures)
- design critical field experiments (DYCOMS)
- Implement the findings in Large-scale models (ECMWF)
- Critically evaluate the result on a global scale (ISSCP,CERES,SSMI)

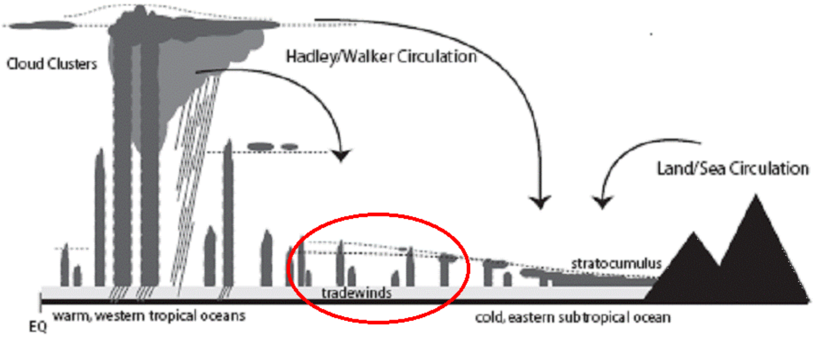
LES results

S. Krueger, Univ of Utah

Conclusions (stratocumulus)

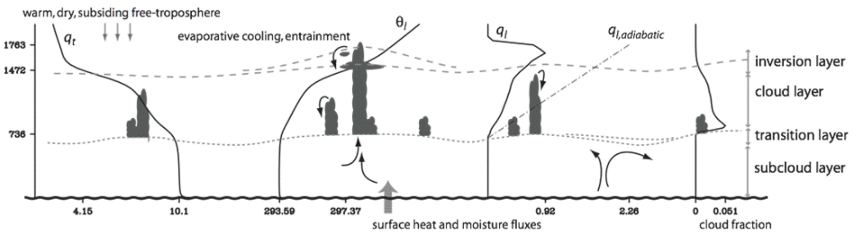
- Mixing in Scu should be done in moist conserved variables
- Key problems : Regime changes : Break up of Scu / decoupling
- For higher(vertical) resolution (dz~100m), TKE-schemes without explicit top-entrainment seem to be an acceptable alternative for parameterizations with explicit top-entrainment parameterizations.

Key Cloud-types that have been studied in GCCS

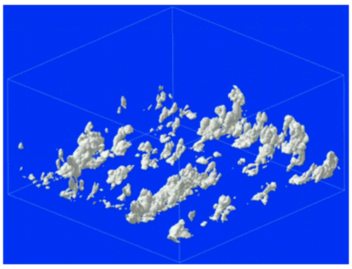


Shallow Cumulus: Characteristics

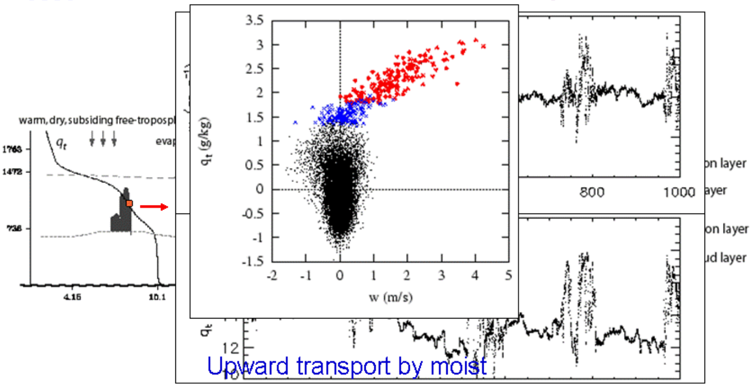
Courtesy Bjorn Stevens



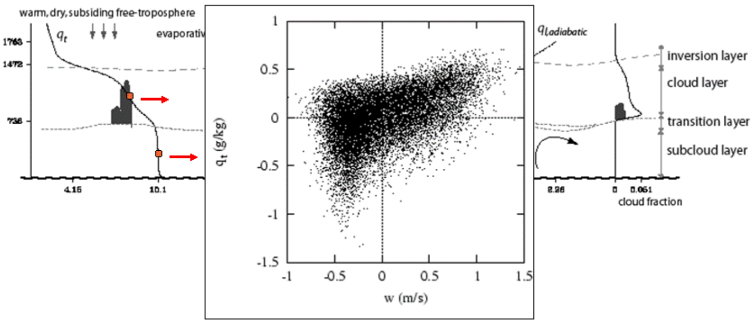
LES
Heus
TU Delft



Horizontal Variability



Upward transport by moist buoyant cumulus cores

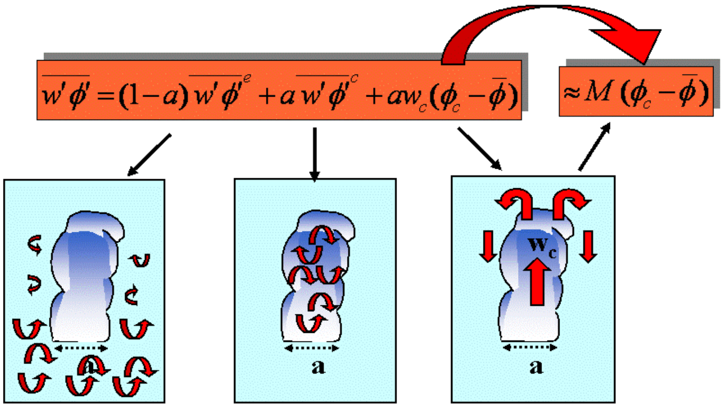


less distinct updrafts in subcloud layer

••••

Strong bimodal character of joint pdf has inspired the design of mass flux parameterizations of turbulent flux in Large scale models

(Betts 1973, Arakawa& Schubert 1974, Tiedtke 1988)



$$\overline{w'\phi'} = (1-a)\overline{w'\phi'}^{e} + a\overline{w'\phi'}^{c} + aw_c(\phi_c - \bar{\phi}) \qquad \approx M(\phi_c - \bar{\phi})$$

How to estimate updraft fields and mass flux?

The old working horse:

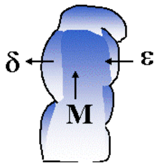
Betts	1974 JAS
Arakawa&Schubert	1974 JAS
Tiedtke	1988 MWR
Gregory & Rowntree	1990 MWR
Kain & Fritsch	1990 JAS
And many more........	

Entraining plume model:

$$\frac{\partial \phi_c}{\partial z} = -\varepsilon(\phi_c - \bar{\phi}) \text{ for } \phi \in \{\theta_l, q_t\}$$

$$\frac{1}{M}\frac{\partial M}{\partial z} = \varepsilon - \delta$$

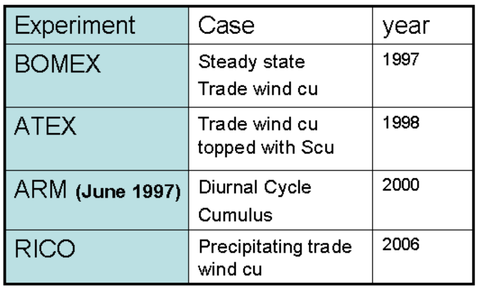
$$\frac{1}{2}\frac{\partial w_c^2}{\partial z} = -b\varepsilon w_c^2 + aB, \quad B = \frac{g}{\theta_0}(\theta_v - \bar{\theta}_v)$$



Plus boundary conditions at cloud base.

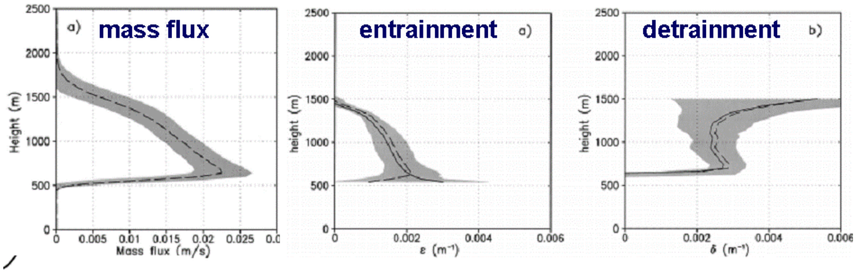
••••

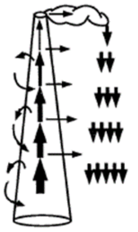
GCSS cases



Experiment	Case	year
BOMEX	Steady state Trade wind cu	1997
ATEX	Trade wind cu topped with Scu	1998
ARM **(June 1997)**	Diurnal Cycle Cumulus	2000
RICO	Precipitating trade wind cu	2006

Typical LES results from GCSS intercomparison studies



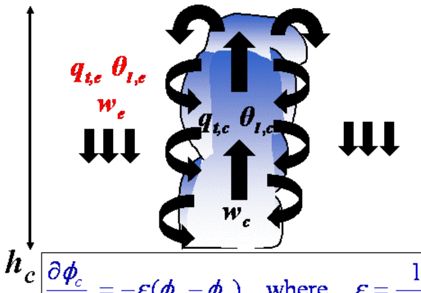


Main Results:

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

Siebesma and Cuypers JAS 95
Siebesma 1998
Grant and Brown QJRMS 1999
Gregory QJRMS 2000
Neggers et al JAS 2002

Led to simple conceptual models for entrainment rates



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

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

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

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

Siebesma 1997
Bretherton and Grenier JAS 2003

Shallow convection: h_c ~ 1000m

ε ~10^{-3} m^{-1} !!

Alternative: $\boxed{\varepsilon \approx \frac{1}{w_c \tau_0} \propto \frac{1}{w_c}}$

Neggers et al 2001 JAS
Cheinet 2003 JAS

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

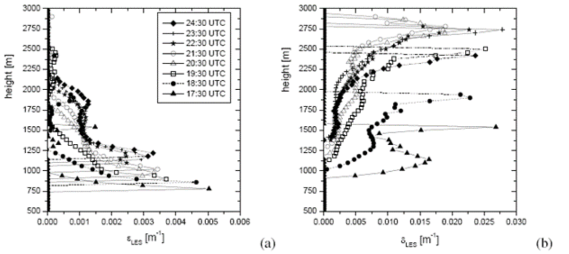
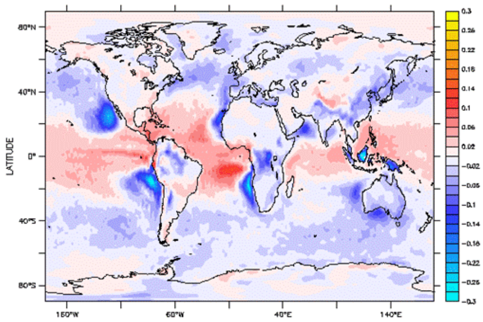


FIGURE 3: Hourly averaged fractional entrainment (a) and detrainment (b) rates diagnosed from LES results for the ARM case. Note the different x-axis scale for (a) and (b).

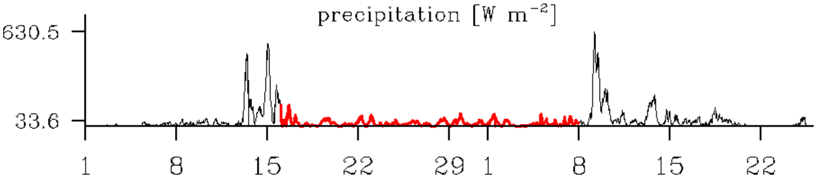
Sensitivities in ECMWF

Change in cloudcover when setting the entrainment rate of the updraft in the subcloud layer to zero:

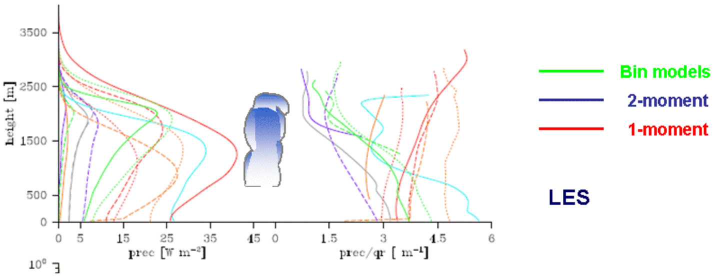


Intercomparison case based on precipitating cumulus observed during field campaign RICO:

- **Period: 2004 December 16 – 2005 January**

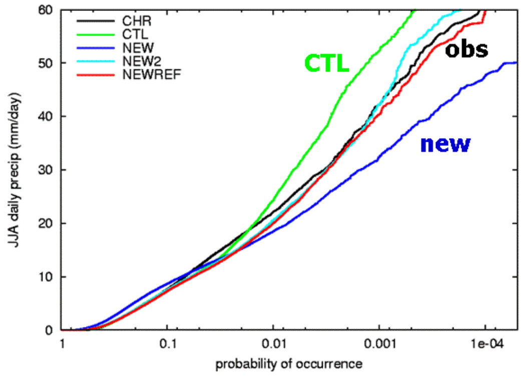


Observed precipitation rate during suppressed period : ~20W/m2 = 0.6 mm/day



Does precipitation from these shallow clouds matter?

Precipitation Histogram of JJA for 1991-1995
for the Rhine catchment area with a regional climate model
(RACMO) (25km resolution)



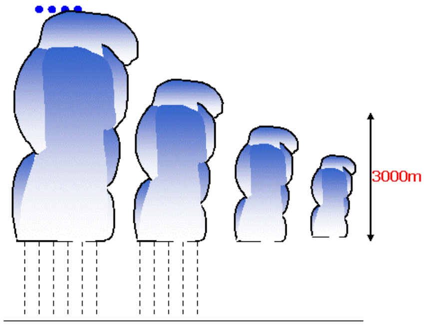
Ctl (23r4) :

- Too few low precipitation rate events.
- Too many high precipitation rate events

Ctl (31r1) :

- Too many low precipitation rate events.
- Too few high precipitation rate events
- Lower extreme events!!

Howcome?



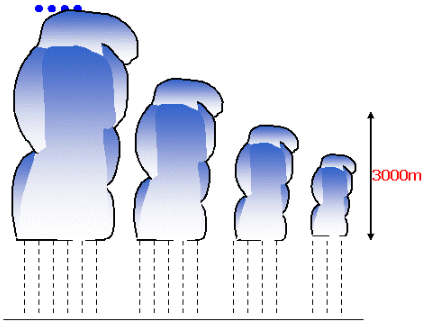
Control (23r4) :

clouds shallower than 3000m are not allowed to precipitate:

- Obviously reduces the "moderate rain intensity events"
- Allows more extreme rain events to build up.

••••

As opposed to..........



New (25r4) :

In which all clouds are allowed to precipitate (if enough ql):

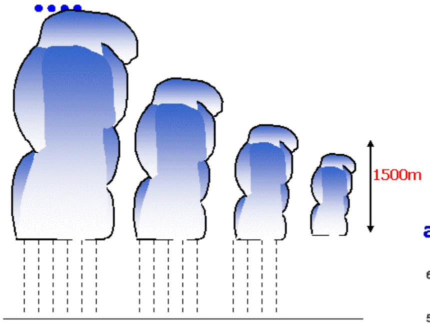
- Obviously encourages the "moderate rain intensity events"
- Prohibits more extreme rain events to build up.

••••

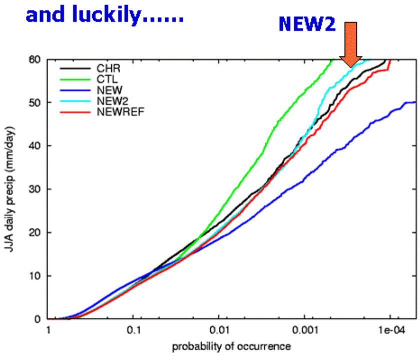
So as a (temporary) fix:

.....One can prohibit clouds of 1500m to precipitate

....



and luckily......

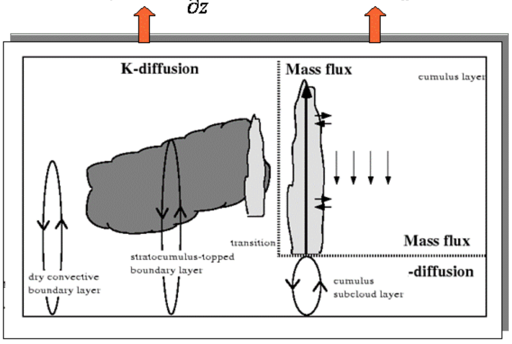


- This merely shows the sensivity of the overall precipation statistics to the precipitation efficiency of shallow clouds!!

....

Standard (schizophrenic) parameterization approach:

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

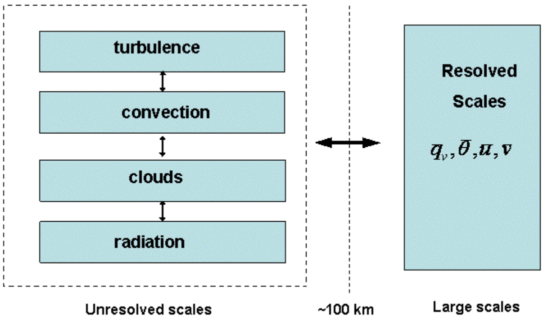


This unwanted situation can lead to:

- Double counting of processes
- Inconsistencies
- Problems with transitions between different regimes:
  - dry pbl ➔ shallow cu
  - scu ➔ shallow cu
  - shallow cu ➔deep cu

....

Intermezzo (2)



turbulence

convection

clouds

radiation

Resolved Scales

q_v, θ, u, v

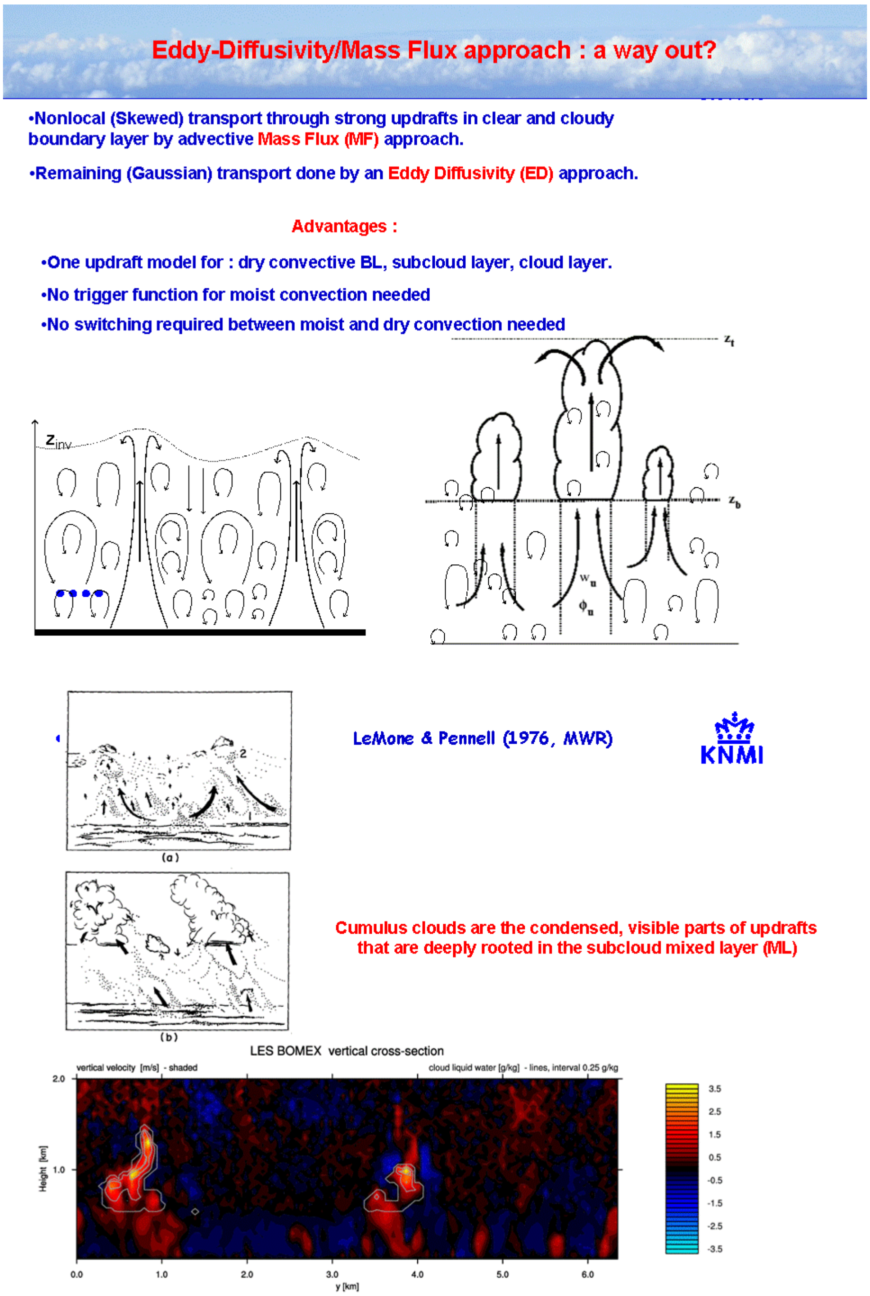
Unresolved scales

~100 km

Large scales

Increase consistency between the parameterizations!

How?



Eddy-Diffusivity/Mass Flux approach : a way out?

- 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.

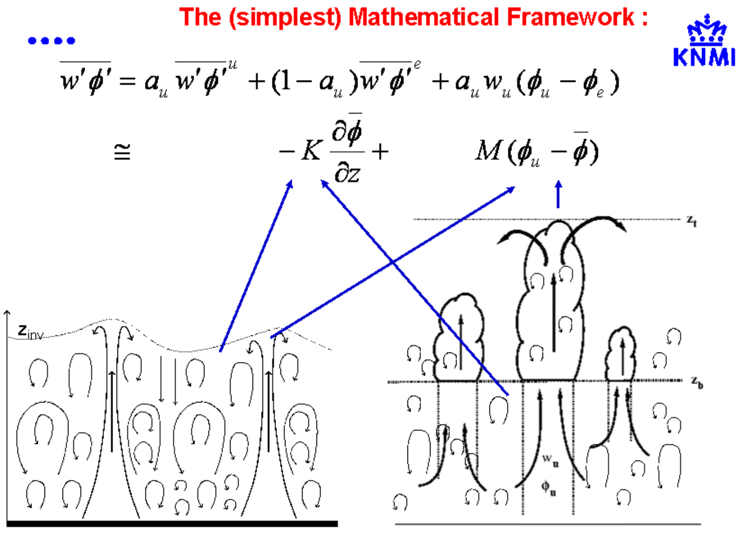
Advantages :

- One updraft model for : dry convective BL, subcloud layer, cloud layer.
- No trigger function for moist convection needed
- No switching required between moist and dry convection needed

LeMone & Pennell (1976, MWR)

Cumulus clouds are the condensed, visible parts of updrafts that are deeply rooted in the subcloud mixed layer (ML)

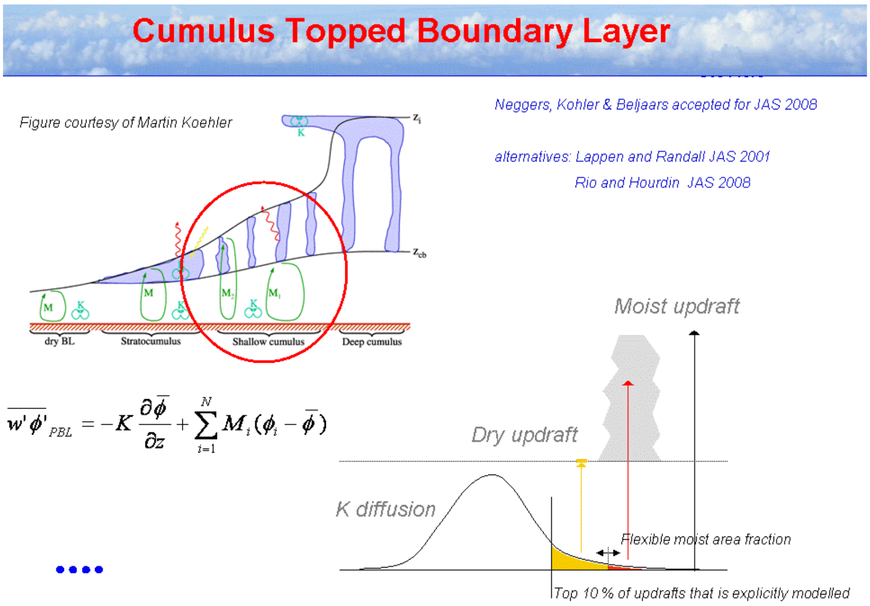
LES BOMEX vertical cross-section



The (simplest) Mathematical Framework :

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

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



Cumulus Topped Boundary Layer

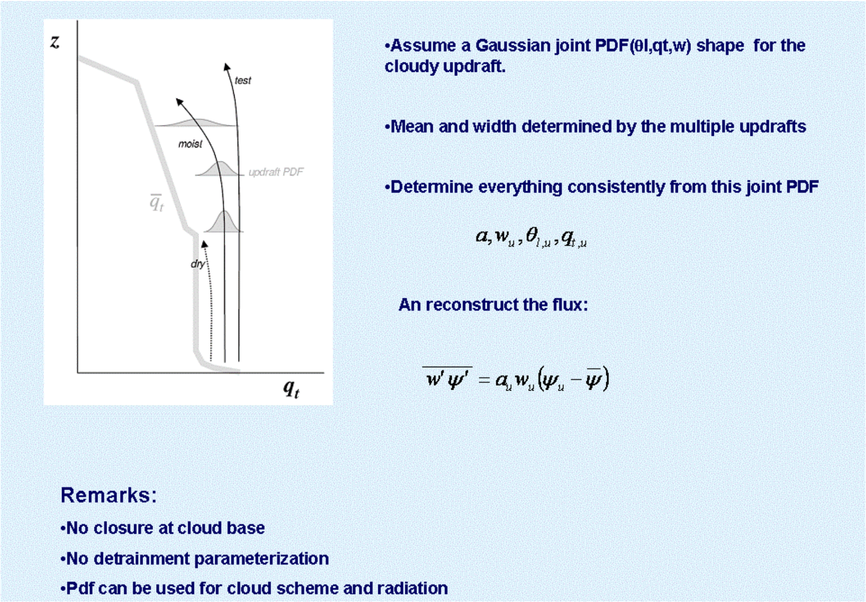
Figure courtesy of Martin Koehler

Neggers, Kohler & Beljaars accepted for JAS 2008

alternatives: Lappen and Randall JAS 2001
Rio and Hourdin JAS 2008

$$\overline{w'\phi'}_{PBL} = -K\frac{\partial\overline{\phi}}{\partial z} + \sum_{i=1}^{N} M_i(\phi_i - \overline{\phi})$$

••••



- •Assume a Gaussian joint PDF(θl,qt,w) shape for the cloudy updraft.
- •Mean and width determined by the multiple updrafts
- •Determine everything consistently from this joint PDF

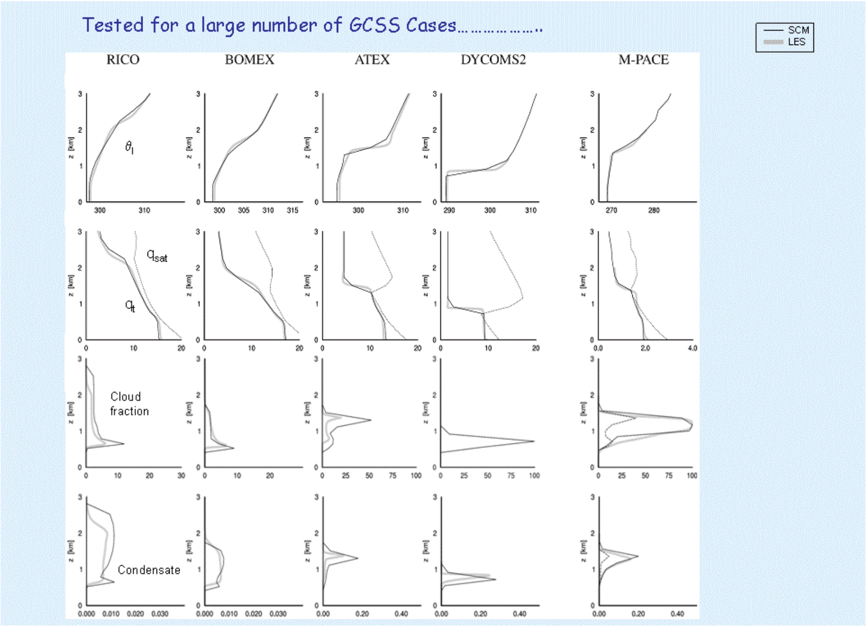
$$a, w_u, \theta_{l,u}, q_{t,u}$$

An reconstruct the flux:

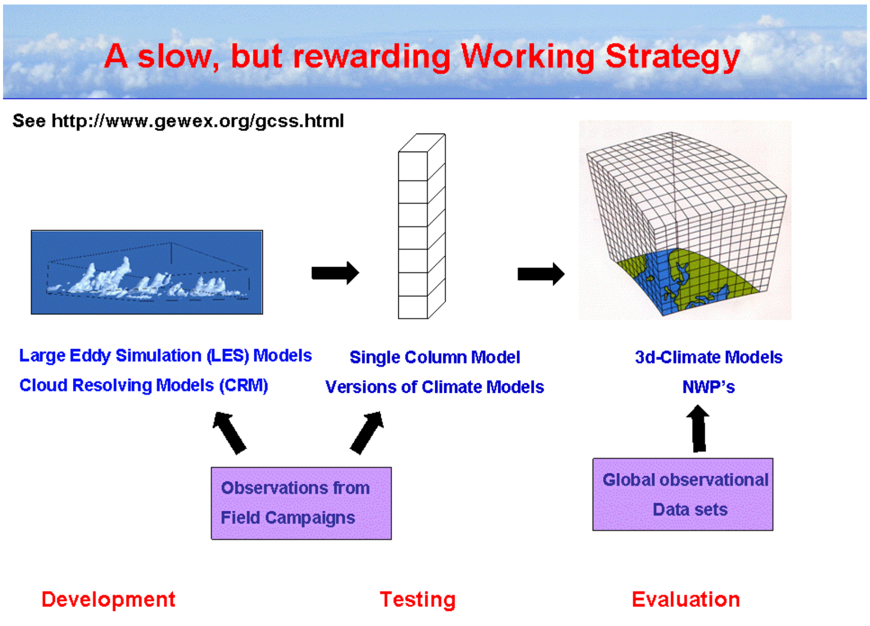
$$\overline{w'\psi'} = a_u w_u(\psi_u - \overline{\psi})$$

Remarks:

- •No closure at cloud base
- •No detrainment parameterization
- •Pdf can be used for cloud scheme and radiation



Tested for a large number of GCSS Cases………………..



A slow, but rewarding Working Strategy

See http://www.gewex.org/gcss.html

Large Eddy Simulation (LES) Models
Cloud Resolving Models (CRM)

Single Column Model
Versions of Climate Models

3d-Climate Models
NWP's

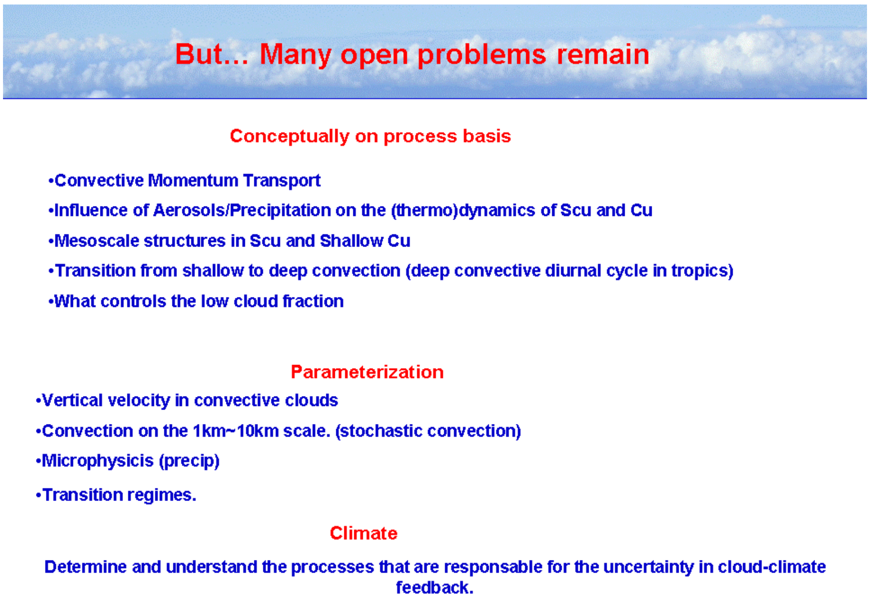
Observations from
Field Campaigns

Global observational
Data sets

Development

Testing

Evaluation



But… Many open problems remain

Conceptually on process basis

- •Convective Momentum Transport
- •Influence of Aerosols/Precipitation on the (thermo)dynamics of Scu and Cu
- •Mesoscale structures in Scu and Shallow Cu
- •Transition from shallow to deep convection (deep convective diurnal cycle in tropics)
- •What controls the low cloud fraction

Parameterization

- •Vertical velocity in convective clouds
- •Convection on the 1km~10km scale. (stochastic convection)
- •Microphysicis (precip)
- •Transition regimes.

Climate

Determine and understand the processes that are responsable for the uncertainty in cloud-climate feedback.