Representation of Cloud Processes in Large Scale Models

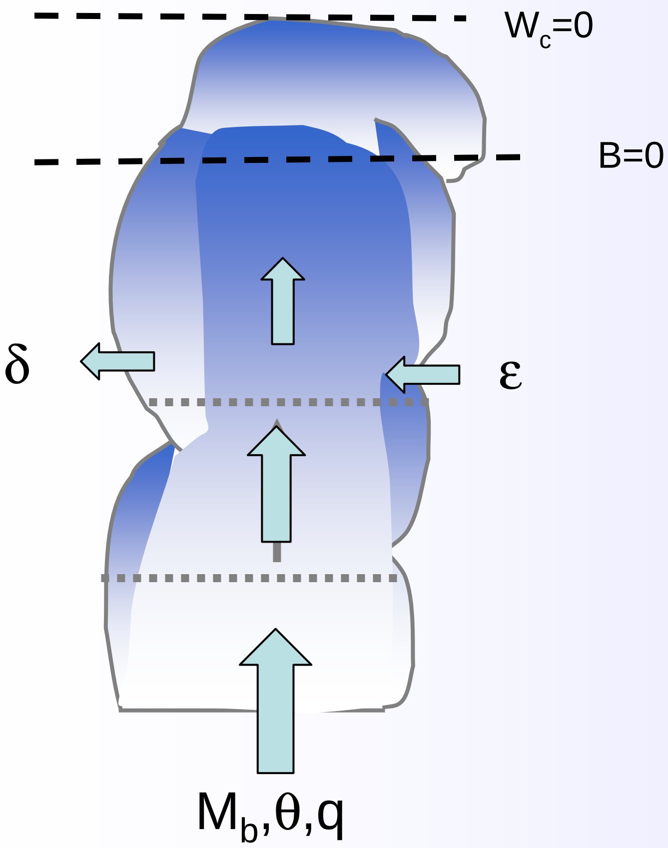
Lecture 3

Cloud Parameterizations

Outlook

A. Pier Siebesma

All nice and fine, but…….



We need to know:

1. What is the entrainment and detrainment
2. At which height does the cloud stop (wc-equation)
3. What are the values of M ,θ, q at cloud base (Closure)
4. When does convection initiate (triggering)

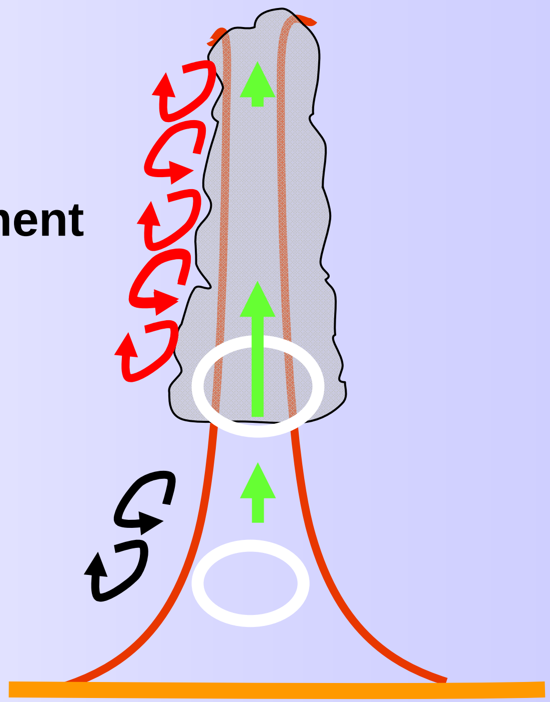
1.

Vertical Velocity In Cumulus Convection

Why?

- Overshoot
- Triggering
- Mass Flux $M \sim w_c\ \sigma$
- not all CMIP5 models use wc-eq

Entrainment



This equation can be derived from the updraft equation where it is assumed that the pressure gradient term is absorbed in a “reduction” factor of the buoyancy.

$$w_u \frac{\partial w_u}{\partial z} = -b\varepsilon w_u{}^2 + aB$$

Vertical velocity

A wide range of realisations

$$w_u \frac{\partial w_u}{\partial z} = -b\varepsilon {w_u}^2 + aB$$

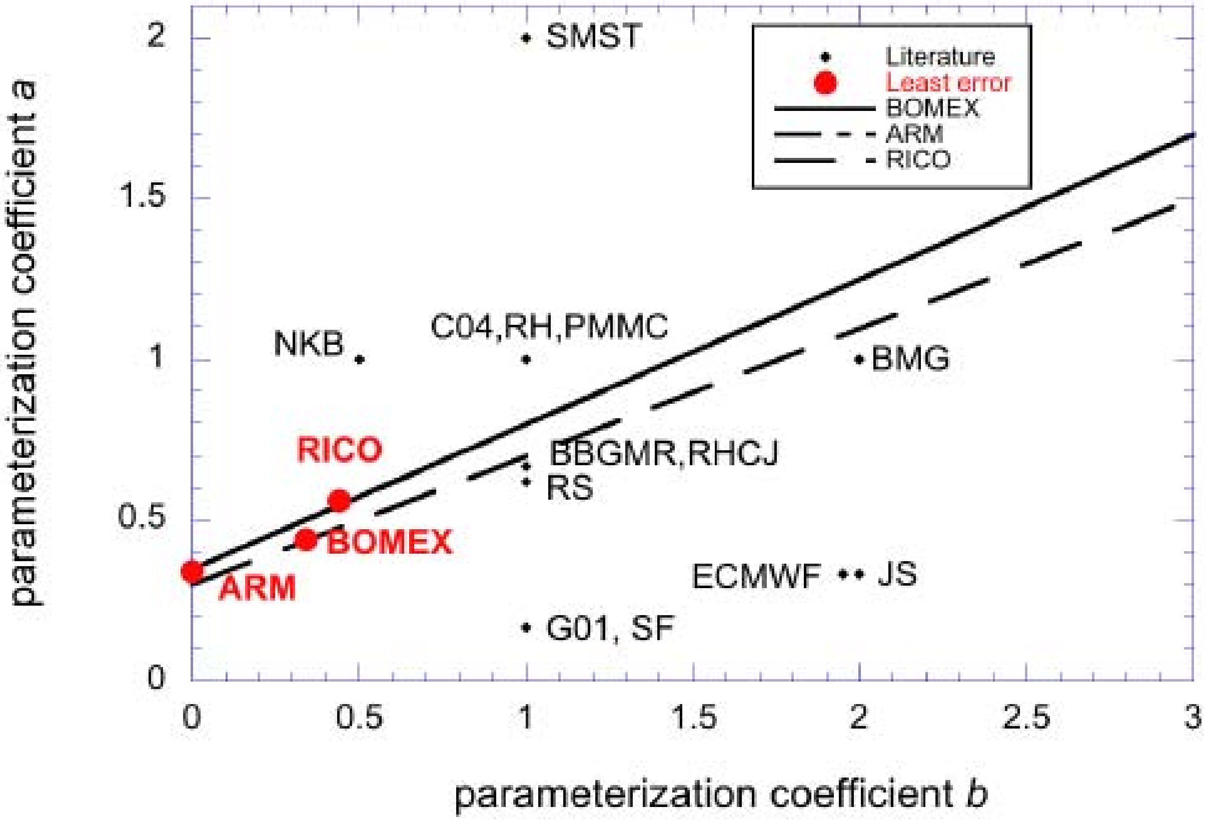
Reference	Acronym	Eq.	a	b	Remarks
Simpson and Wiggert (1969)		(1)	$\frac{2}{3}$		$\frac{1}{2}\frac{\partial w_c^2}{\partial z} = aB_c - 0.18\frac{w_c^2}{R}$, R is cloud radius
Bechtold et al. (2001)	BBGMR	(12)	$\frac{2}{3}$	1	
Gregory (2001)	G01	(11)	$\frac{1}{6}$	1	$\frac{1}{2}\frac{\partial w_c^2}{\partial z} = aB_c - (b'\delta + b\epsilon)w_c^2, b' = \frac{1}{2}$
Von Salzen and McFarlane (2002)	SF	(29)	$\frac{1}{6}$	1	
Jakob and Siebesma (2003)	JS	(7)	$\frac{1}{3}$	2	
Bretherton et al. (2004)	BMG	(17)	1	2	
Cheinet (2004)	C04	(1)	1	1	
Soares et al. (2004)	SMST	(6)	2	1	
Rio and Hourdin (2008)	RH	(5)	1	1	$\frac{\partial \sigma w_c^2}{\partial z} = a\sigma B_c - b'\delta\sigma w_c^2, b' = \frac{1}{2}$
					b value found after substitution of Eq. (4)
Neggers et al. (2009)	NKB	(12)	1	$\frac{1}{2}$	$\frac{1}{2}(1-2\mu)\frac{\partial w_c^2}{\partial z} = aB_c - b\epsilon w_c^2, \mu = 0.15$
Pergaud et al. (2009)	PMMC	(7)	1	1	
Rio et al. (2010)	RHCJ	(9)	$\frac{2}{3}$	1	$\frac{1}{2}\frac{\partial w_c^2}{\partial z} = aB_c - (b' + b\epsilon)w_c^2, b' = 0.002$
De Rooy and Siebesma (2010)	RS	(27)	0.62	1	
ECMWF c36r1 (2010)	ECMWF	(6.9)	$\frac{1}{3}$	1.95	
Kim and Kang (2011)	KK	(11)	$\frac{1}{6}$	2	$\frac{1}{2}\frac{\partial w_c^2}{\partial z} = a(1 - C_\epsilon b)B_c, C_\epsilon = 1/\overline{RH} - 1$

Which one to use?

De Roode et al 2012

optimal parameters a and b estimated from LES simulations

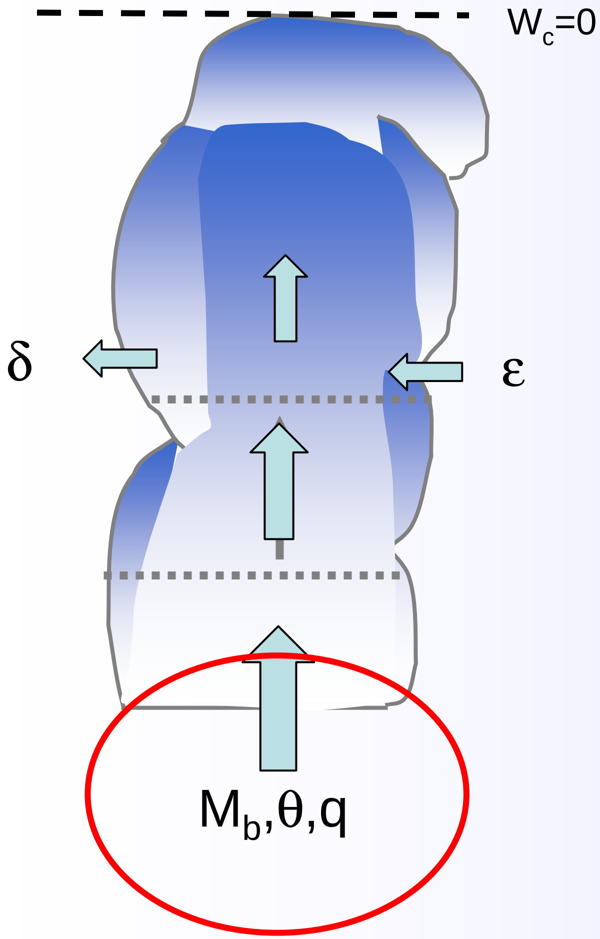
$$w_u \frac{\partial w_u}{\partial z} = -b\varepsilon w_u{}^2 + aB$$



$$w_u \frac{\partial w_u}{\partial z} = \frac{1}{3} B$$

Only 30% of buoyancy is effectively used for transformation to organized vertical velocity.

All nice and fine, but…….



We need to know:

1. What is the entrainment and detrainment
2. At which height does the cloud stop (wc-equation)
3. What are the values of M ,θ, q at cloud base (Closure)
4. When does convection initiate (triggering)

2.

Closure

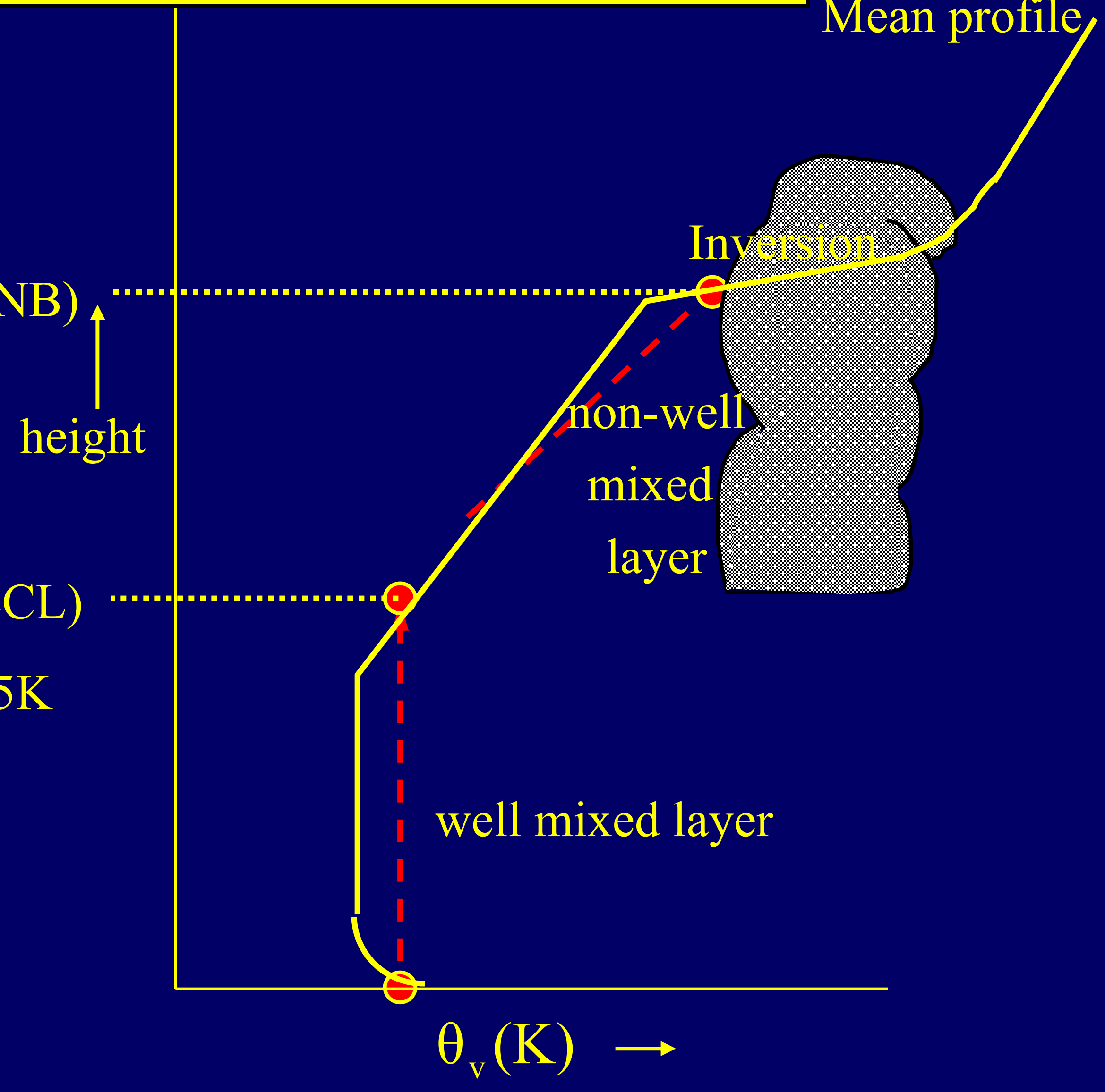
Trigger: usually : simple adiabatic ascent

Level of neutral buoyancy (LNB)

Lifting condensation level (LCL)

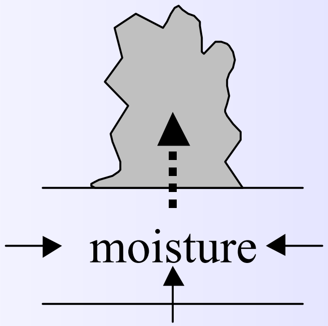
start convection: if $\Delta T > -0.5K$

- w_u cloud base: 1m/s



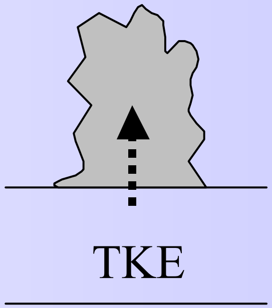
Coupling of M_b to *sub-cloud* layer

(Tiedtke 1989)



$$M_b^c \, (q_t^c - \bar{q}_t)_b = \overline{w'q'}^s + horizontal\ advection$$

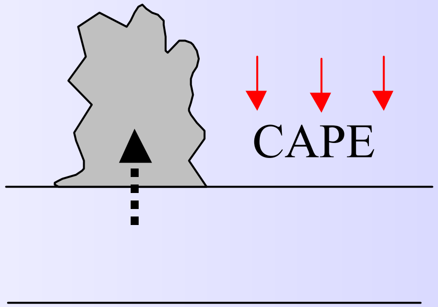
(Grant 1999)



$$M_b{}^c = 0.03 \quad w^*_{sub}$$

Coupling of M_b to *cloud* layer

Fritsch & Chappell (1980)



•The closure gives the *Mb* needed to break down the given amount of CAPE during time t by compensating subsidence.

3.

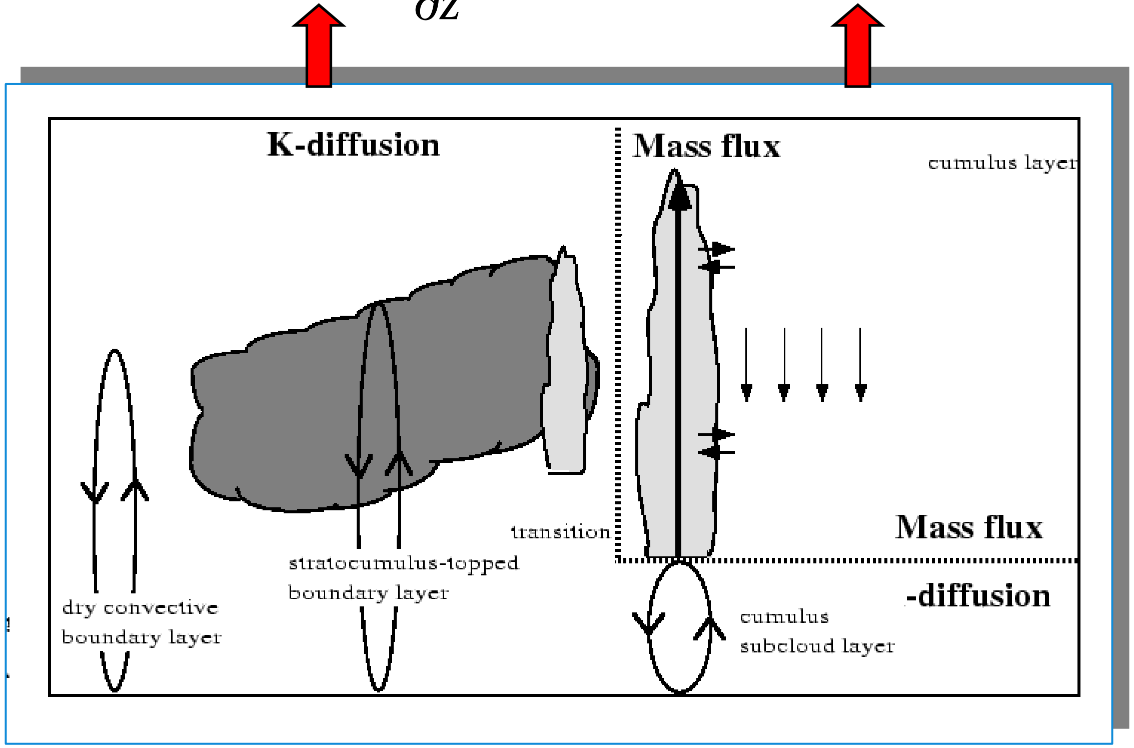
Coupling Transport Schemes

Wrap up

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

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

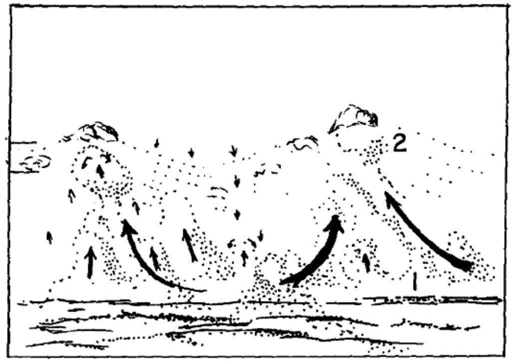
$$\frac{\partial \overline{\phi}}{\partial t} \cong -\frac{\partial}{\partial z}\left(\overline{w'\phi'}\right) + \overline{S}$$



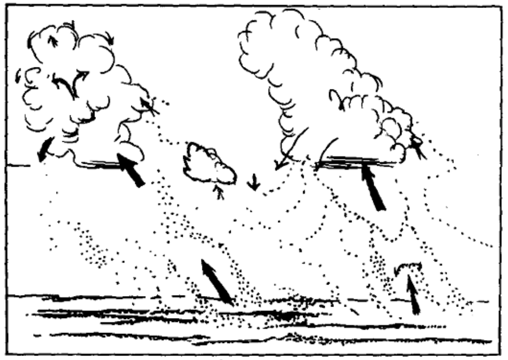
Problems with transitions between different regimes:

- dry pbl ➔ shallow cu
- scu ➔ shallow cu
- shallow cu ➔deep cu

Courtesy: Stephan de Roode



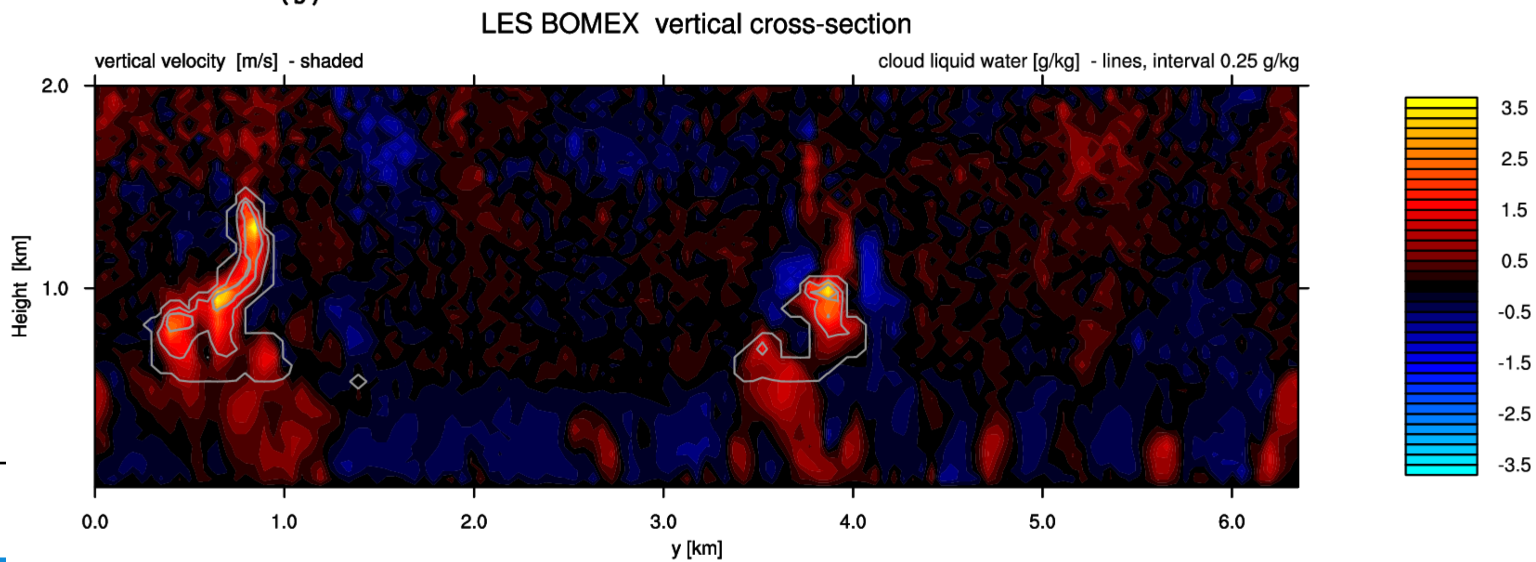
(a)



(b)

- **LeMone & Pennell (1976, MWR)**

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



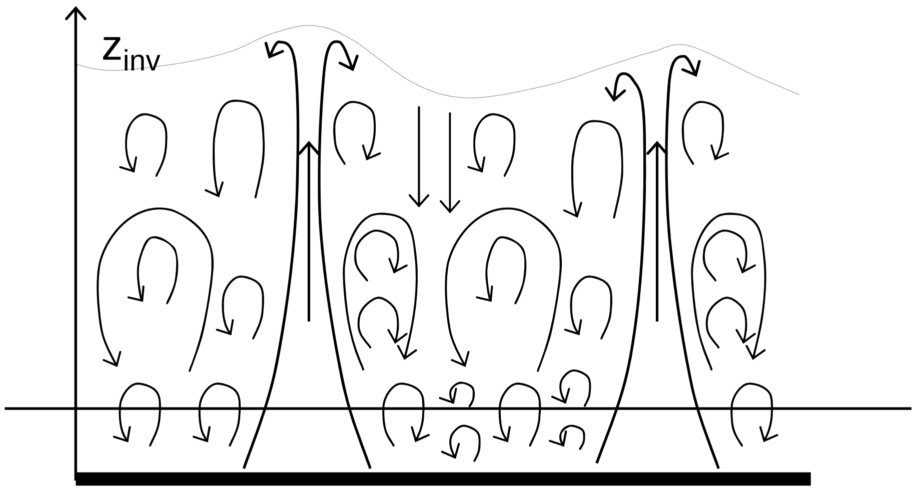
Eddy-Diffusivity/Mass Flux (EDMF) approach

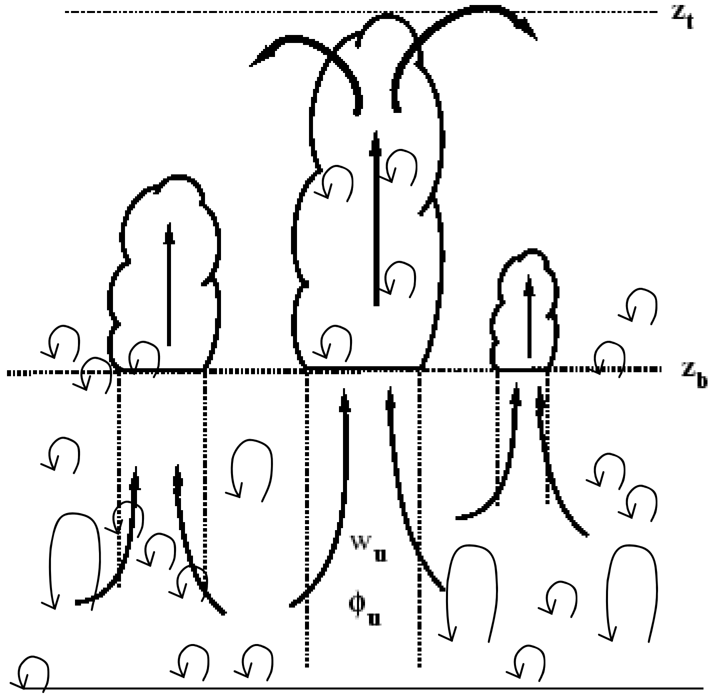
•Nonlocal (Skewed) transport through strong updrafts in clear and cloudy boundary layer by advective Mass Flux (MF) approach.

•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 and cloud base height closure for moist convection needed
- No switching required between moist and dry convection needed





The (simplest) Mathematical Parameterization Framework :

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

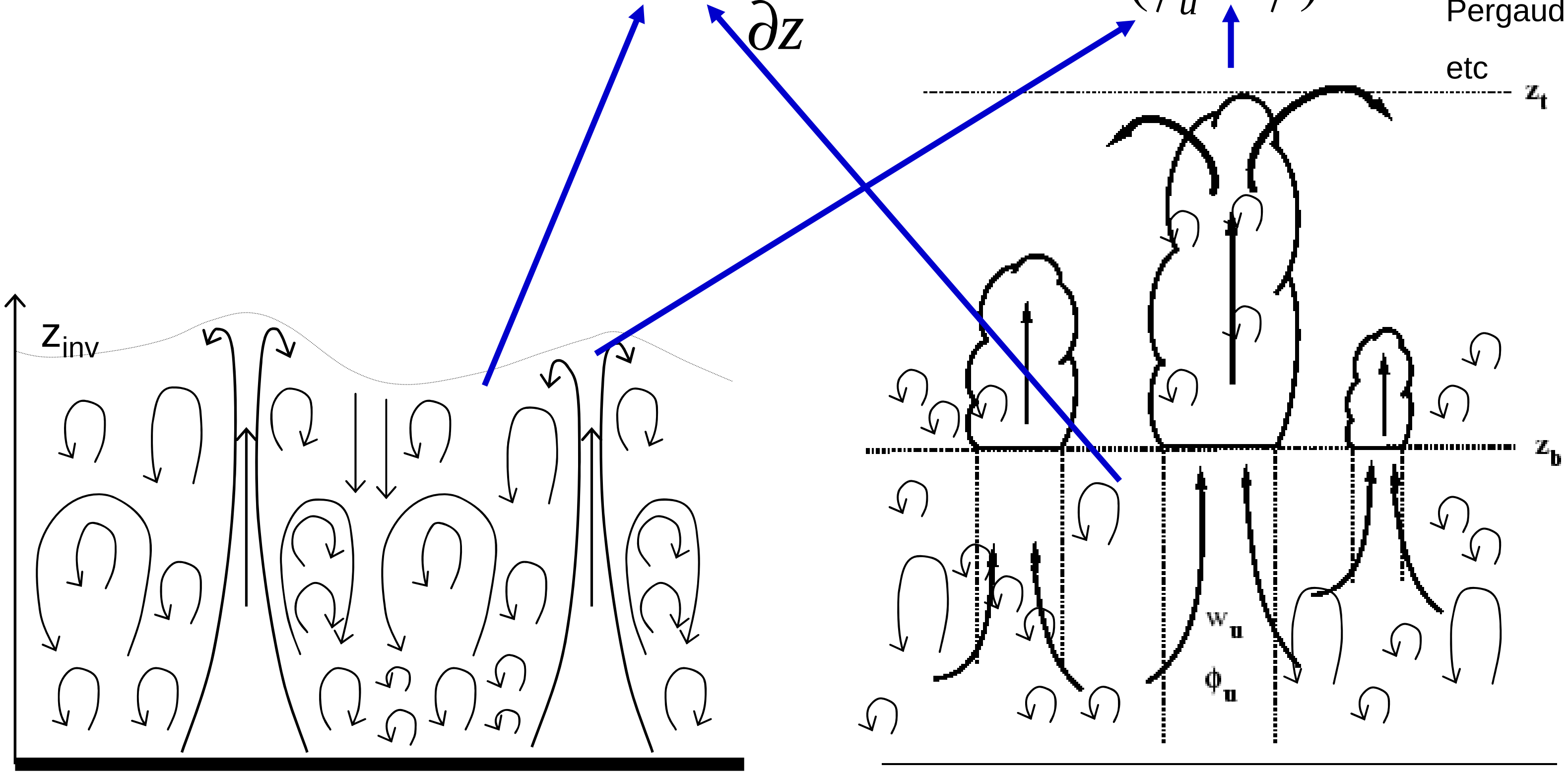
$$\cong \quad -K\frac{\partial\overline{\phi}}{\partial z} + \quad M(\phi_u - \overline{\phi})$$

siebesma&teixeira 2000

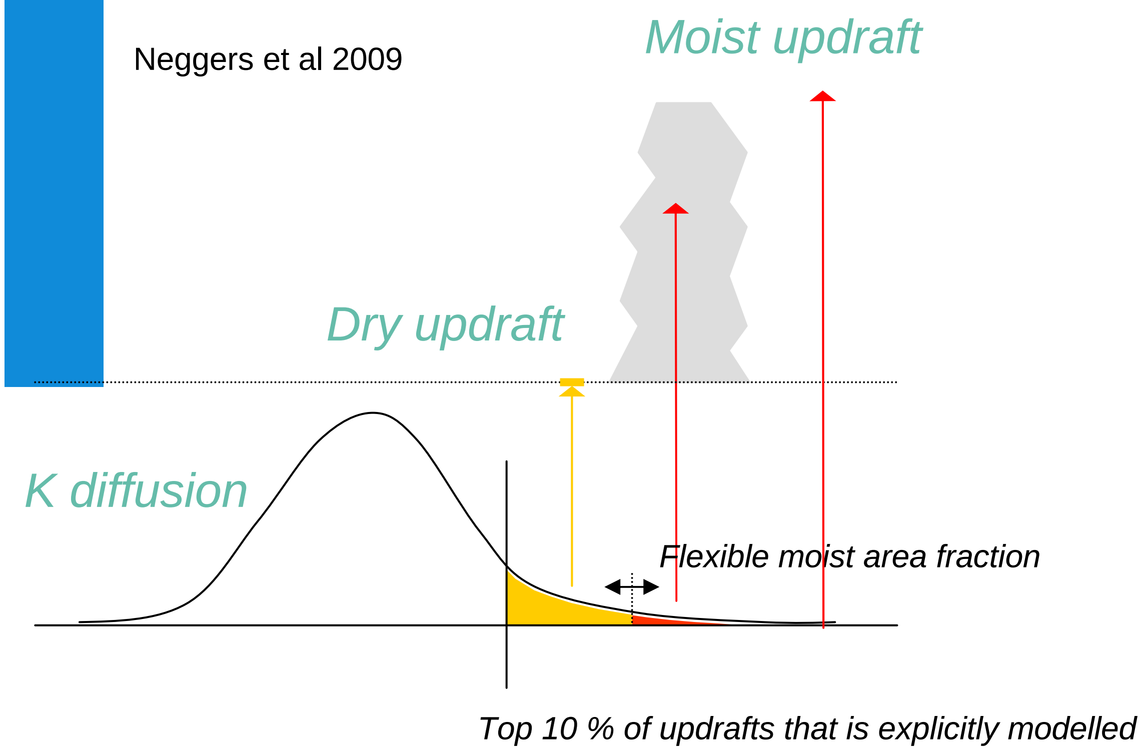
Hourdin et al 2002

Pergaud 2006

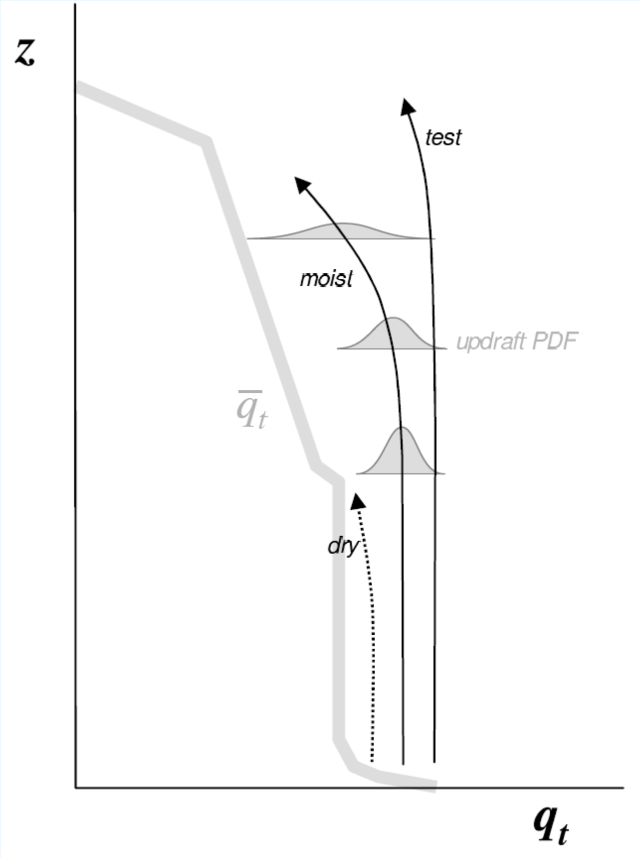
etc



Neggers et al 2009



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



•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

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

An reconstruct the flux:

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

Remarks:

•No closure at cloud base

•No detrainment parameterization

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

4.

Cloud Schemes

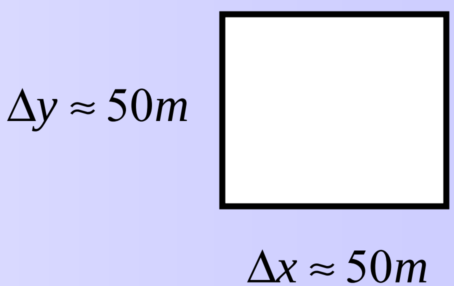
Why do we need a cloud scheme?

Why do we need a cloud scheme?

- Cloud radiative effects
    - cloud fraction
    - cloud condensate (cloud water and ice)

- Latent Heat Effects (condensation/evaporation effects, precipitation)
    - These effects are usually referred to as "large scale" (i.e.large scale precipation) the other contribution residing form the convection schemes (convective precipiation). The distinction is rather arbitrary and depend on the model design, resolution etc…..)

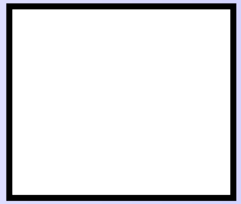
How do we build such a scheme?



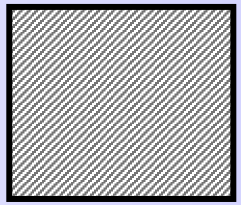
Cloud Schemes in LES

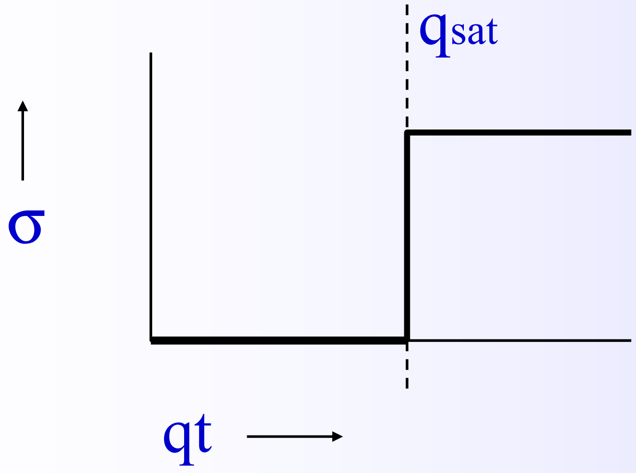
- Simple: All or Nothing:

$$\begin{cases} \sigma_c = 0, \\ q_c = 0, \qquad\qquad \text{if} \quad \overline{q}_t - \overline{q}_{sl} < 0 \end{cases}$$



$$\begin{cases} \sigma_c = 1, \\ q_l = \alpha(q_t - q_{sl}), \quad \text{if} \quad q_t - q_{sl} > 0 \end{cases}$$





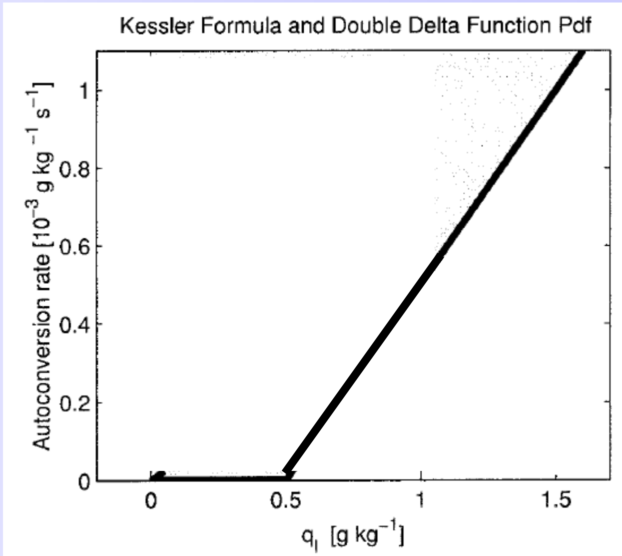
Cloud adjustment

Autoconversion (transition from cloud water to rain)

$$\left(\frac{\partial q_r}{\partial t}\right)_{au} = G_p$$

Autoconversion (Kessler, 1969)

$$G_P = \begin{cases} k_0\left(q_c - q_{c,crit}\right) & \text{if } q_l > q_{l,crit} \\ 0 & \text{otherwise} \end{cases}$$



Many different formulations
(including dependencies on cloud droplet number density)

Autoconversion:

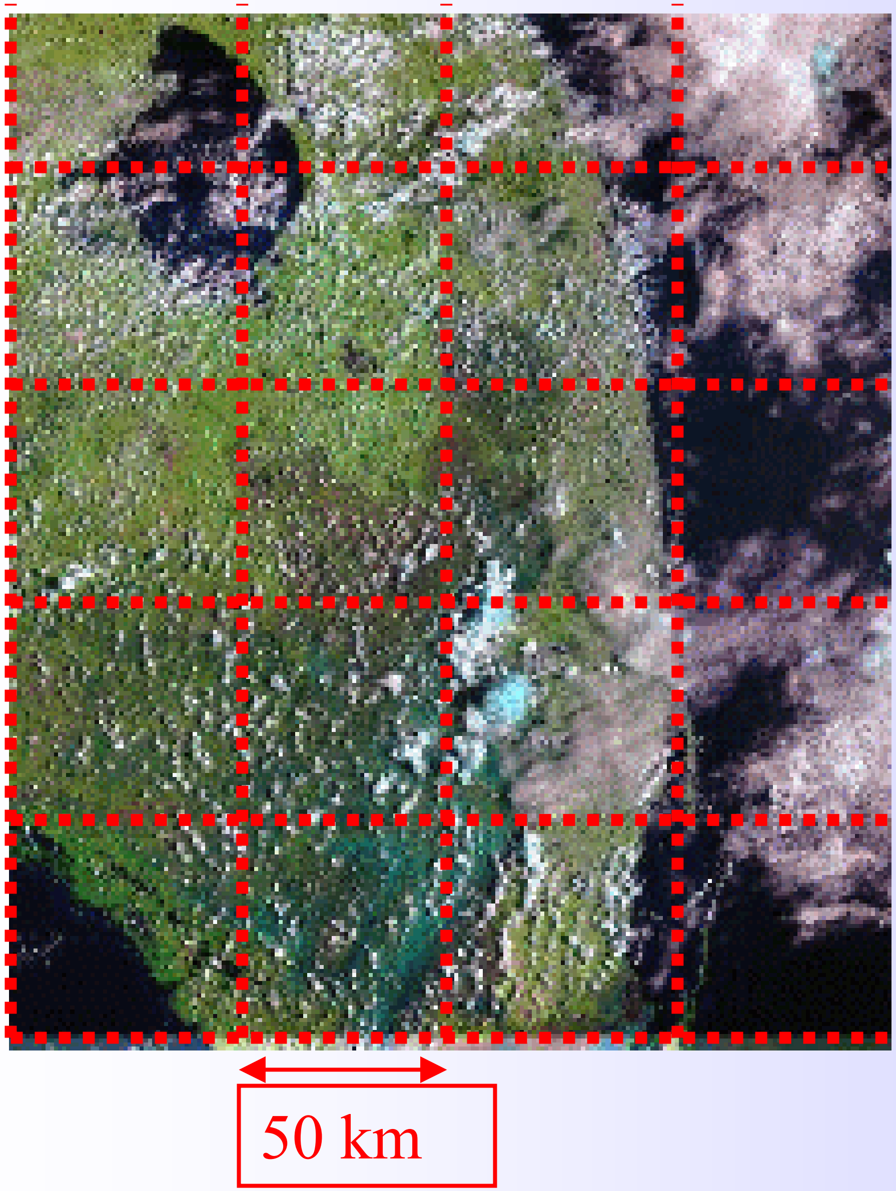
$$\left(\frac{\partial q_r}{\partial t}\right)_{auto} = k_0 q_c^{\,a} N_c^{\,-b} T$$

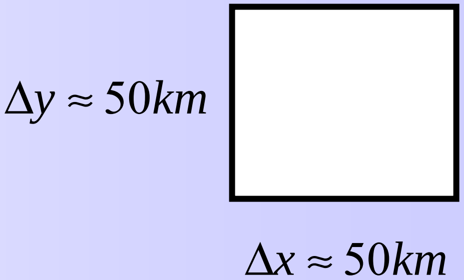
$N_{aerosol}$

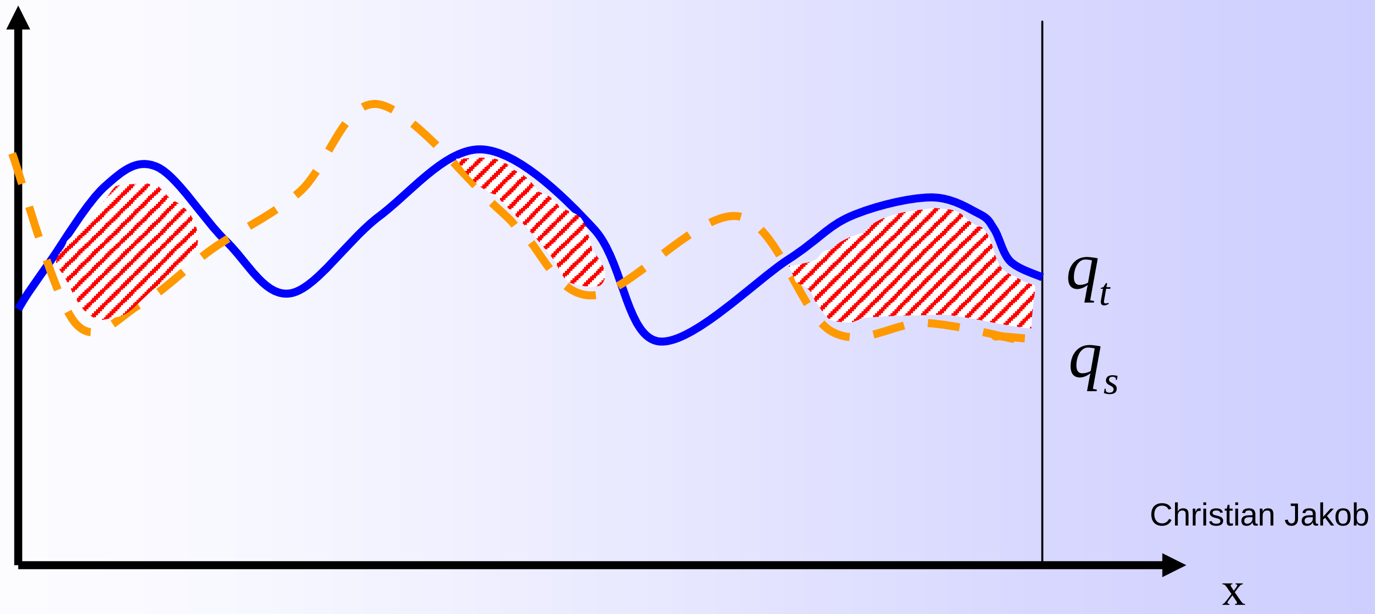
q_c	N_c	T	
1		H	Kessler (1969)
1		exp	Sundqvist (1978)
2.47	-1.79		Khairoutdinov and Kogan (2000)
4.7	-3.3		Beheng (1994)
4	-2		Seifert and Beheng (2001)
2.33	-0.33	H	Tripoli and Cotton (2000)
2.33	-0.33	H	Liu and Daum (2006)
2.74	-1.35		.

Specific choice of the autoconversion is often used to calibrate the TOA global energy budget

But does this work for coarser resolutions?



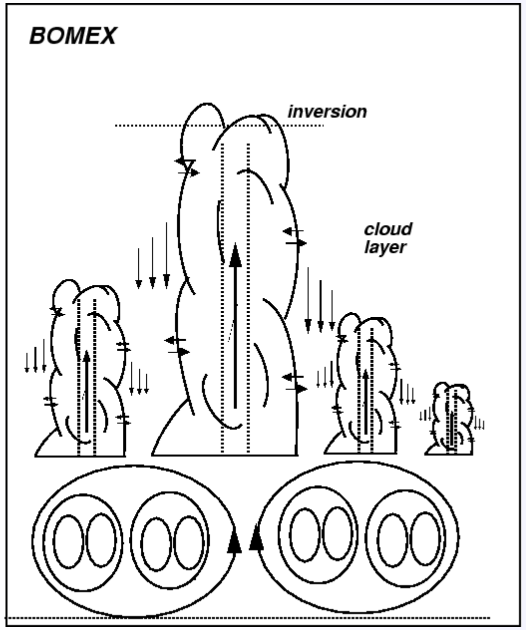


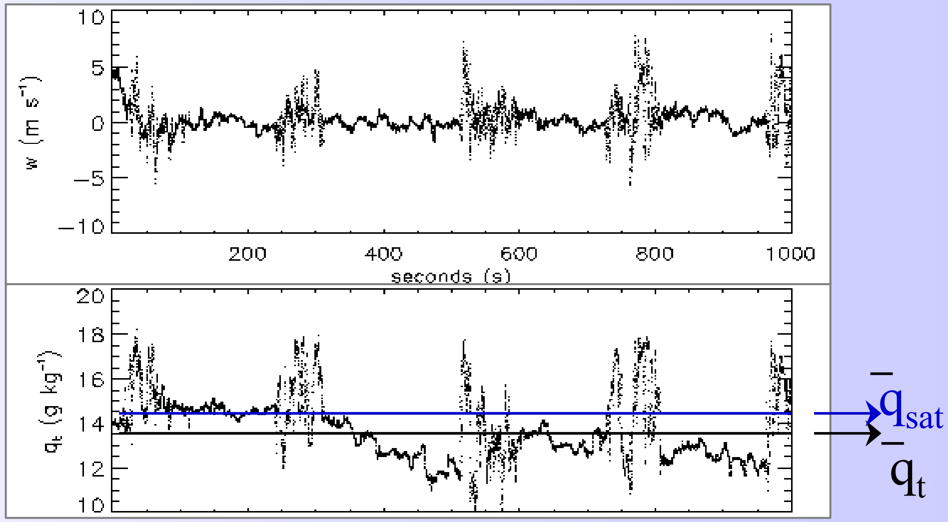


• Due to subgrid variability of humidity and temperature only parts of the grid box are oversaturated (and hence cloudy).

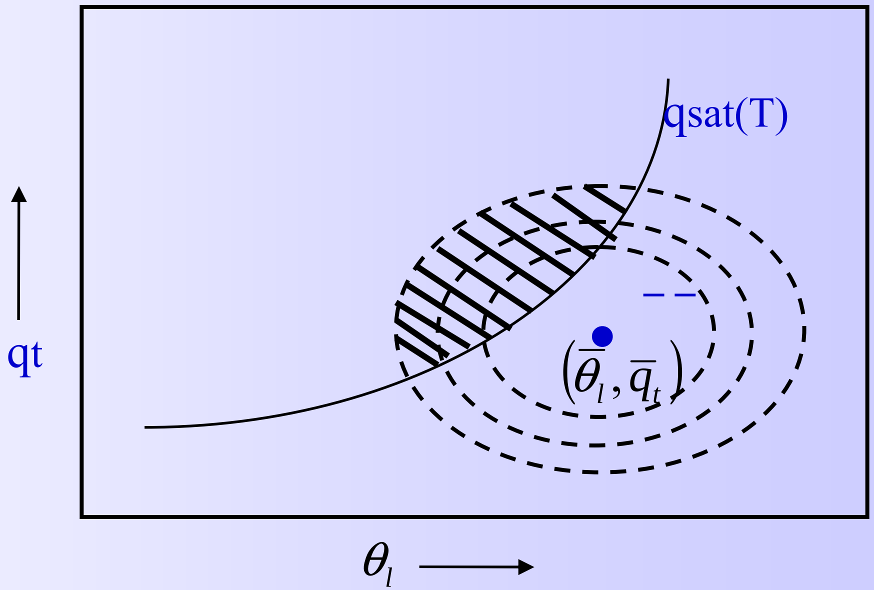
• So we can have clouds in a gridbox even if the mean RH in the gridbox <1.

So…. "All or Nothing" does not work if the resolution does not resolve clouds!!!!





Joint Probability Distribution of θl and qt



Let's assume we know this Joint pdf

$$
\begin{aligned}
a_c &= \int\int H(q_t - q_s) P(\theta_\ell, q_t) dq_t d\theta_\ell \\
q_l &= \int\int (q_t - q_s) H(q_t - q_s) P(\theta_\ell, q_t) dq_t d\theta_\ell
\end{aligned} \quad (3)
$$

with $H(x) = \begin{cases} 0, & x < 0 \\ 1, & x > 0 \end{cases}$

Convenient to introduce:

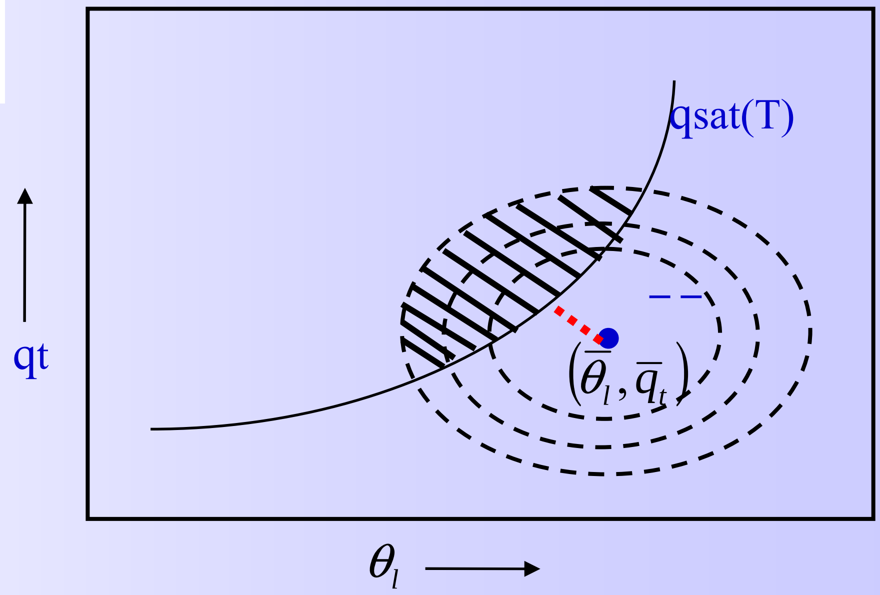
"The distance to the saturation curve"

$$s = q_t - q_s(p, T)$$

Normalise s by its variance

$$t \equiv s/\sigma_s$$

$$\sigma_s^2 = \overline{s'^2} = a^2\overline{q_t'^2} - 2ab\overline{q_t'\theta_\ell'} + b^2\overline{\theta_\ell'^2}$$



so that a and q_ℓ can be written in single variable PDF

$$\begin{aligned} a_c &= \int_0^{\infty} G(t)dt \\ \overline{q_\ell}/\sigma_s &= \int_0^{+\infty} tG(t)dt \end{aligned} \tag{9}$$

What to choose for G(t)??

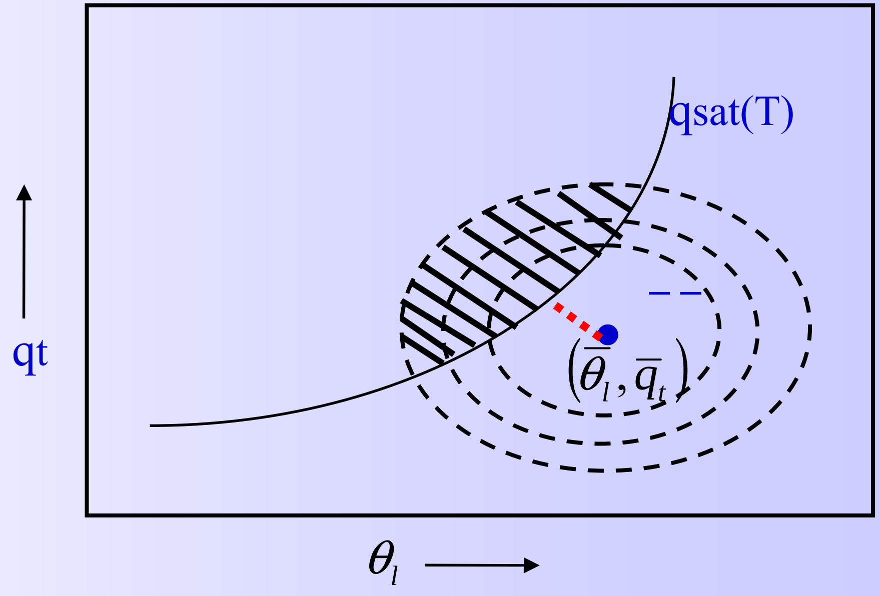
so that a and q_ℓ can be written in single variable PDF

$$\begin{aligned} a_c &= \int_0^{\infty} G(t)dt \\ \overline{q_\ell}/\sigma_s &= \int_0^{+\infty} tG(t)dt \end{aligned} \qquad (9)$$

What to choose for G(t)??

The Gaussian Case

$$G(t)dt = \frac{1}{\sqrt{(2\pi)}} \exp(-t^2/(2))dt \qquad (10)$$



$$a_c = \frac{1}{2}\left(1 + erf\,(\bar{t}/\sqrt{2}\right)$$

$$\frac{\bar{q}_c}{\sigma_s} = \alpha\bar{t} + \sqrt{\frac{1}{2\pi}}\exp\left(\bar{t}^2/2\right)$$

$$Q \equiv \bar{t} = (\bar{q}_t - \bar{q}_s)/\sigma_s$$

So if we know the variance of s (or the variance of qt and θl and its covariance) we know the cloud fraction and the condensed water content.

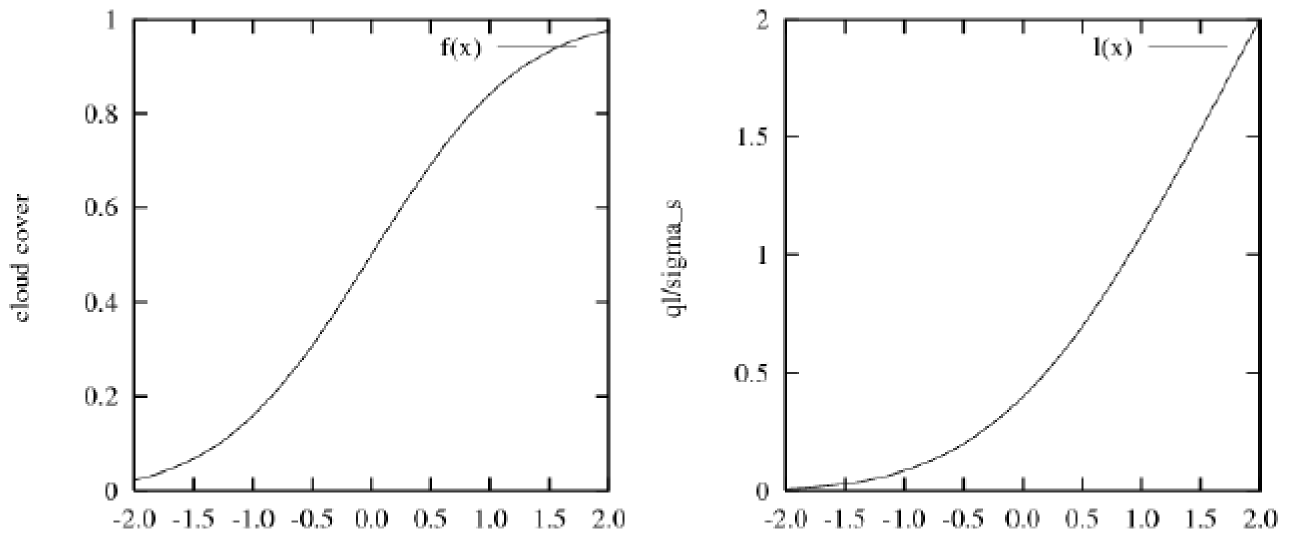
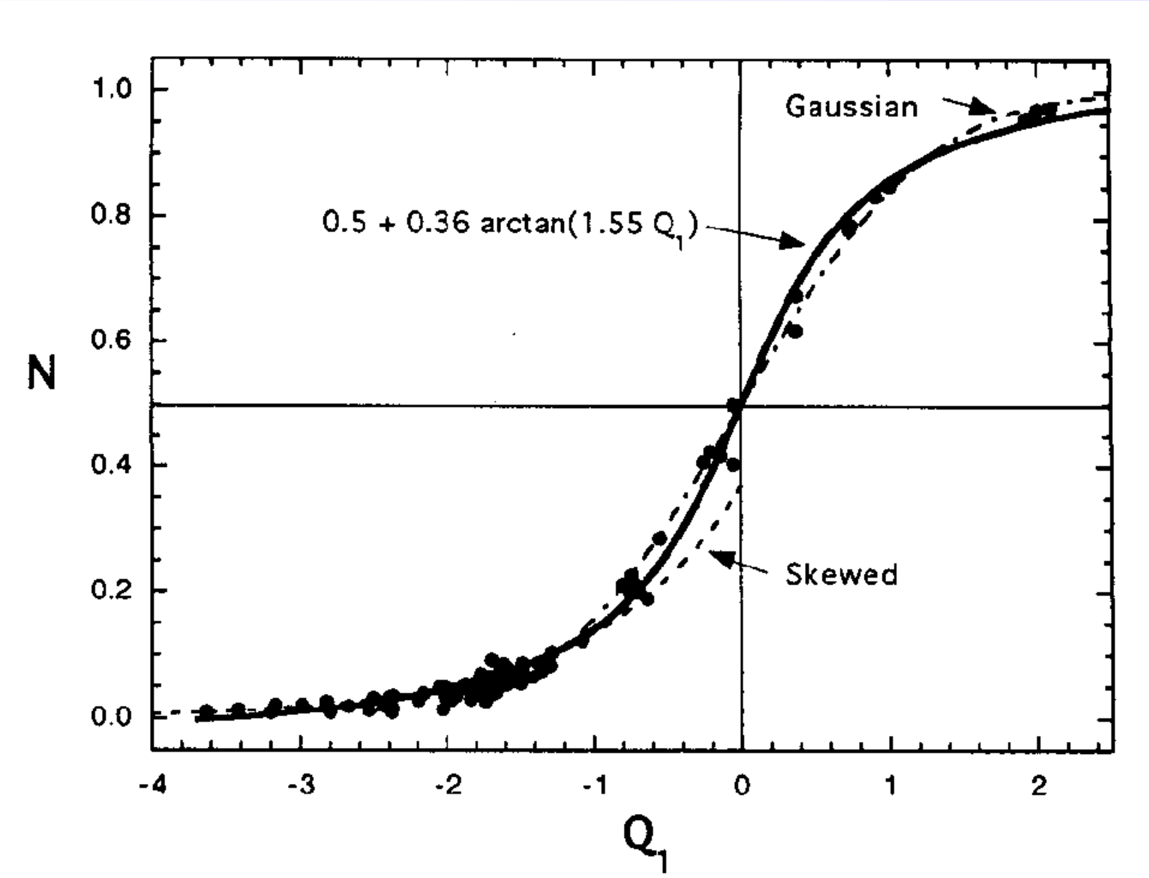


Figure 1:

Evaluation (with LES) (bl-clouds)

Cloud cover

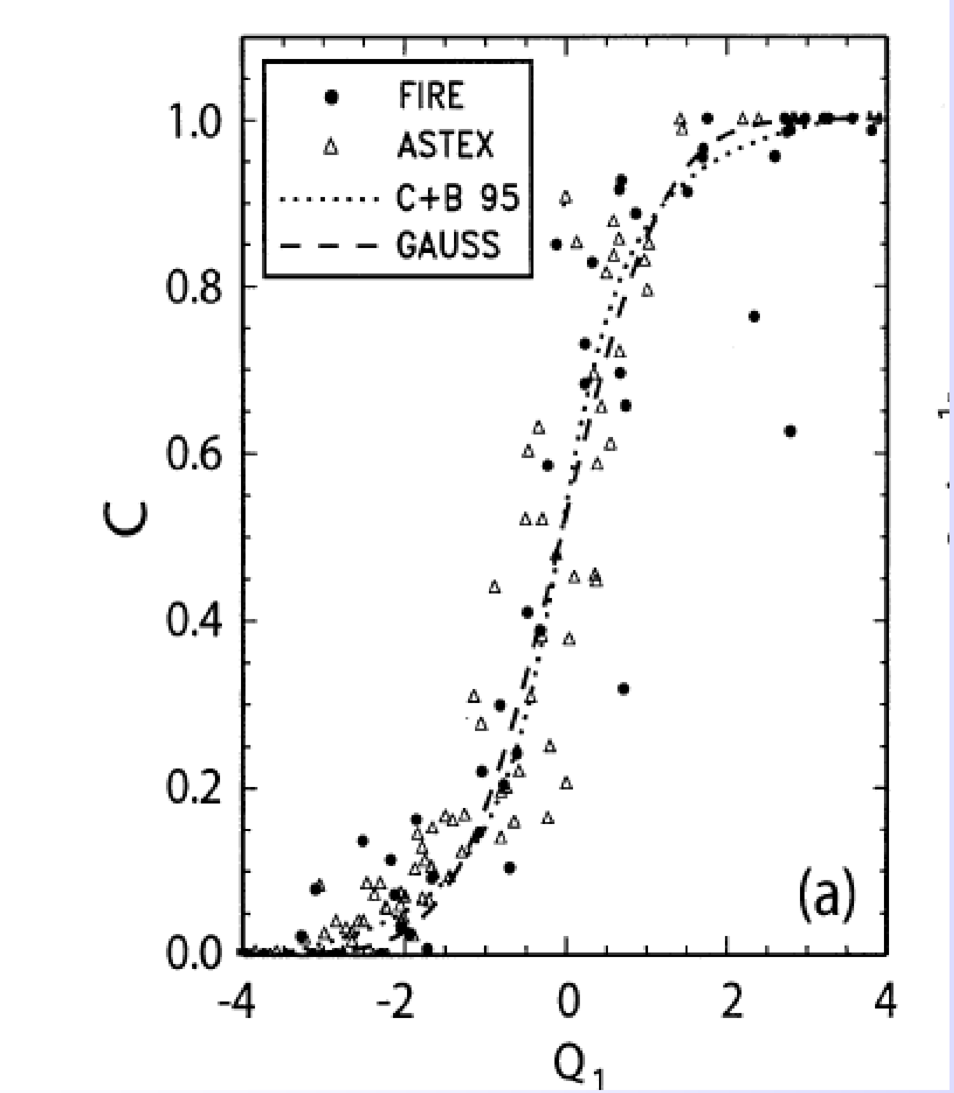


Bechtold and Cuijpers JAS 1995

Bechtold and Siebesma JAS 1999

$$Q \equiv \bar{t} \equiv \frac{\overline{q}_t - \overline{q}_s}{\sigma_s}$$

Evaluation (with obs) (bl-clouds)



(Wood et al 2000)

Remarks:

1. Gaussian PDF “surprisingly good” but many more complicated pdf’s have been proposed (Lewellen and Yoy 1993,Tompkins 2002, Neggers et al 2007, poster Mathias etc etc)

2. Correct limit: if $dx \Rightarrow 0 \; then \, \sigma_s \Rightarrow 0$ and the scheme converges to the all-or-nothing limit

3. Parameterization problem reduced to finding the subgrid variability, i.e. finding σ_s

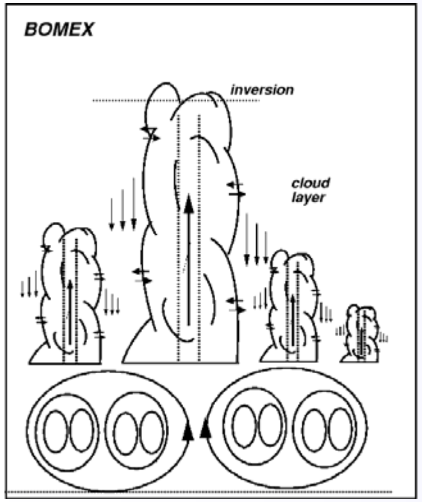
4. For Q<-2 there is essentially zero cloud fraction .

$$RH_{threshold} = 1 - 2\frac{\sigma_s}{q_s}$$

This makes RH-based cloud schemes essentially pdf-based schemes that assume a constant variance

Where does the variance of s originate from?

Where does the variance of s originate from?



Convection and turbulence parameterization should give estimate of σ_s

→

Cloud scheme :

$$a_c = f\left(\frac{\overline{q}_t - \overline{q}_s}{\sigma_s}\right)$$

$$q_l = g\left(\frac{\overline{q}_t - \overline{q}_s}{\sigma_s}\right)$$

Connecting Schemes

Variance equation:

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

production transport dissipation

Simple (diagnostic)

$$M(q_t^{cu} - \overline{q}_t)\frac{\partial \overline{q}_t}{\partial z} \cong \frac{w_*^{cu}}{l_{cloud}} \overline{q_t'^2}$$

(Lenderink and Siebesma 2000)

Works well but no memory: when convection dies out (night) => no variance => no clouds

Complex (prognostic): Tompkins 2002, Neggers 2007, Golaz 2003:

Extra closures needed (the shape of the pdf etc) looks promising implemented in 2 models (ECHAM, GFDL)

But what about cloud adjustment for ice clouds??

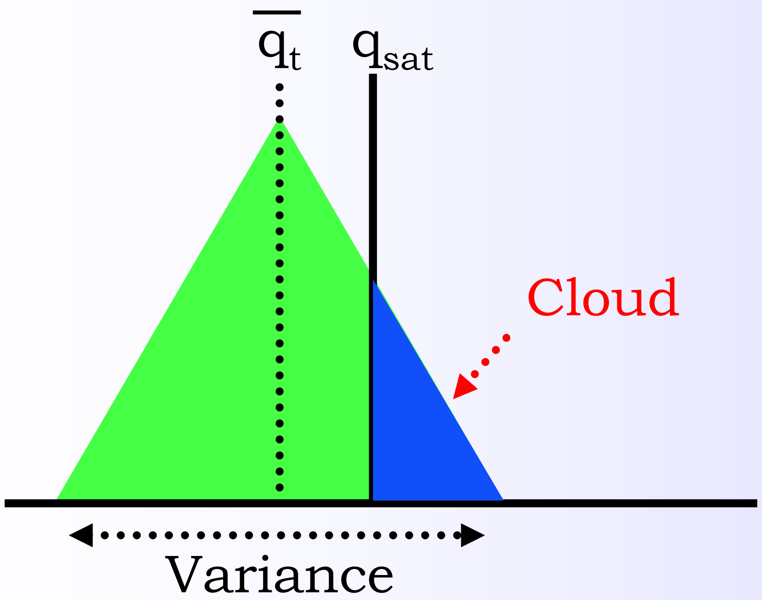
Prognostic statistical PDF scheme:
Which prognostic variables / equations?

Taken from Forbes (ECMWF)

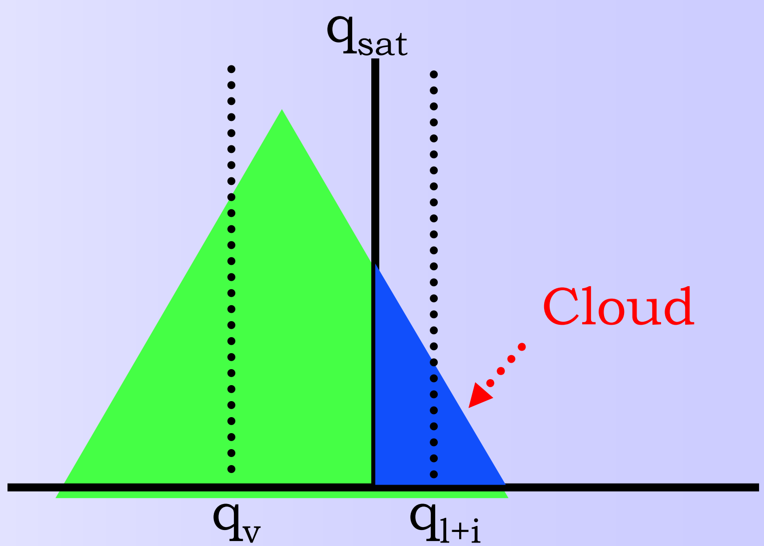
Take a 2 parameter distribution & partially cloudy conditions

(1) Can specify distribution with
- (a) Mean
- (b) Variance of total water

(2) Can specify distribution with
- (a) Water vapour
- (a) Condensed water

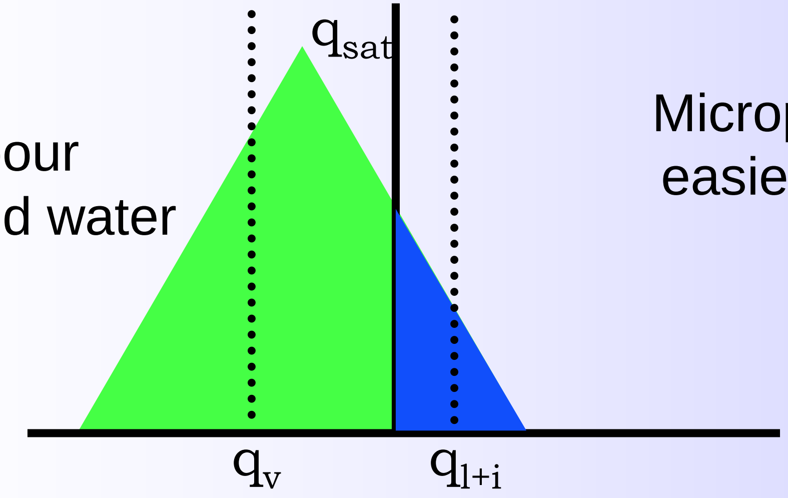


(Tiedtke i.e. 1993)



Prognostic statistical scheme:
(1) Water vapour and cloud water ?

(a) Water vapour
(b) Condensed water

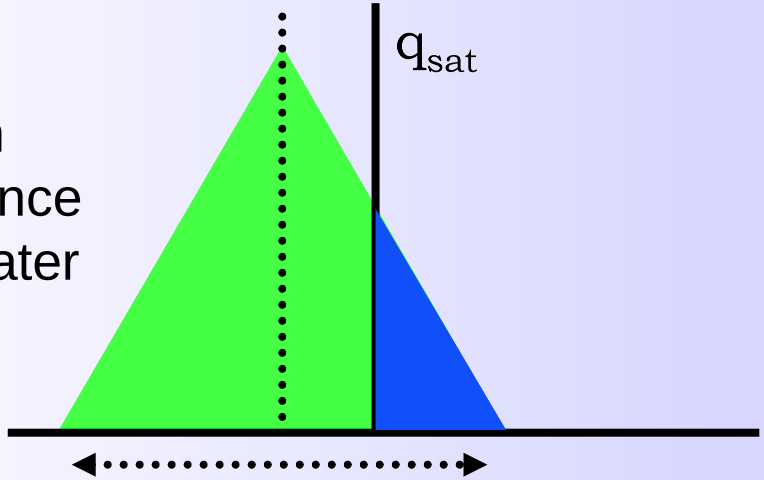


Microphysical sources and sinks easier to parametrize.

But problems arise in...

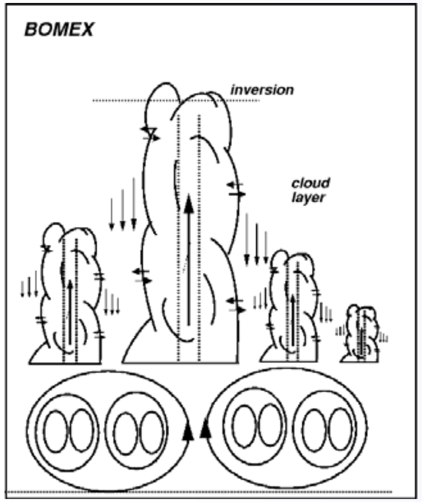
Finding the correct source and sink terms in the q_c equation

Prognostic statistical scheme:
(2) Total water mean and variance ?



(a) Mean
(b) Variance
of total water

- “Cleaner solution”.
- Need to parametrize those tricky microphysics terms!



$$a_c = f\left(\frac{\overline{q}_t - \overline{q}_s}{\sigma_s}\right)$$

$$q_l = g\left(\frac{\overline{q}_t - \overline{q}_s}{\sigma_s}\right)$$

$$R(a_c, \overline{q}_t, \sigma_s)$$

Convection and turbulence parameterization give estimate of σ_s ⟷ **Cloud scheme :** ⟷ **radiation scheme :**

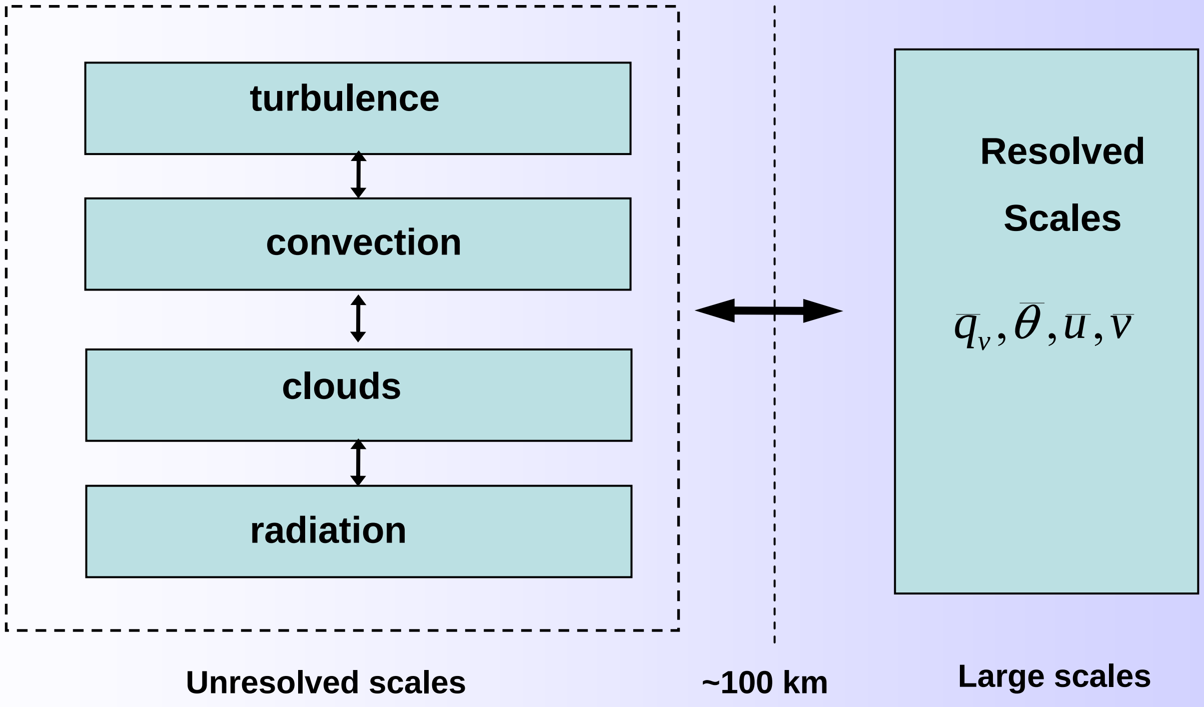
- Schemes interact with each other on the subgrid scale

•Subgrid variability (at least the 2nd moment) for the thermodynamic variables needs to be taken into acount in any GCM for parameterizations of convection, clouds and radiation in a consistent way.

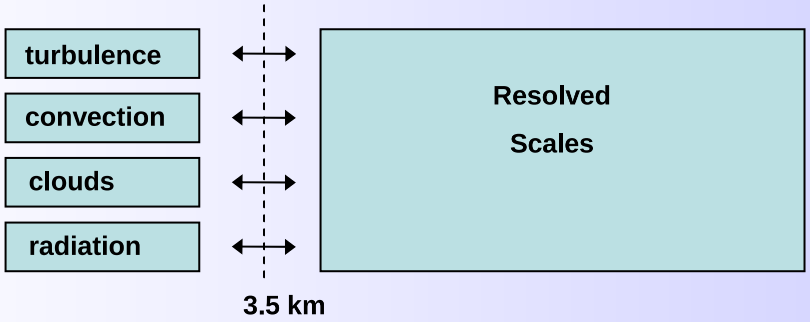
•At present this has not be accomplished in any GCM.

New Pathways

Consistent pdf based parameterizations



Pathway 1: Global Cloud Resolving Modelling (Brute Force)



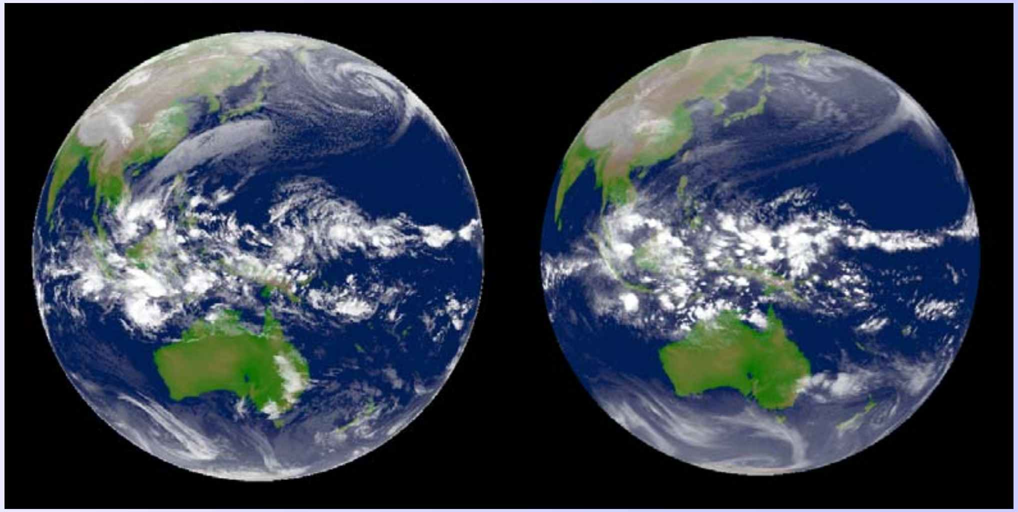
NICAM simulation: MJO DEC2006 Experiment

3.5km run: 7 days from 25 Dec 2006

- ***Short timeslices***
- ***Testbed for interactions:***

deep convection and the large scale

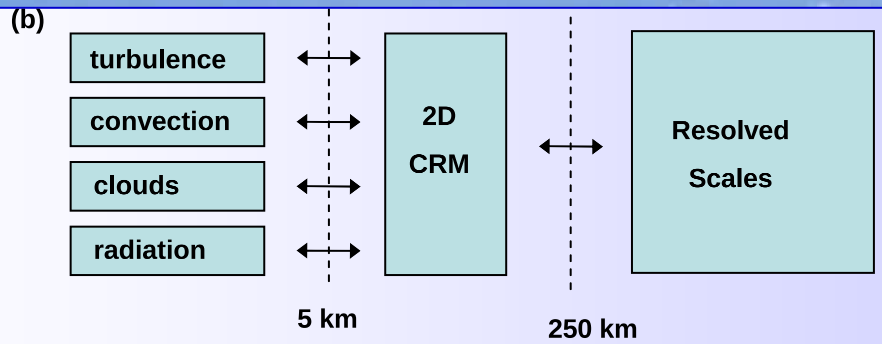
- ***Boundary clouds, turbulence, radiation still unresolved***



MTSAT-1R ***NICAM 3.5km***

Miura et al. (2007, Science)

Pathway 2: Superparameterization

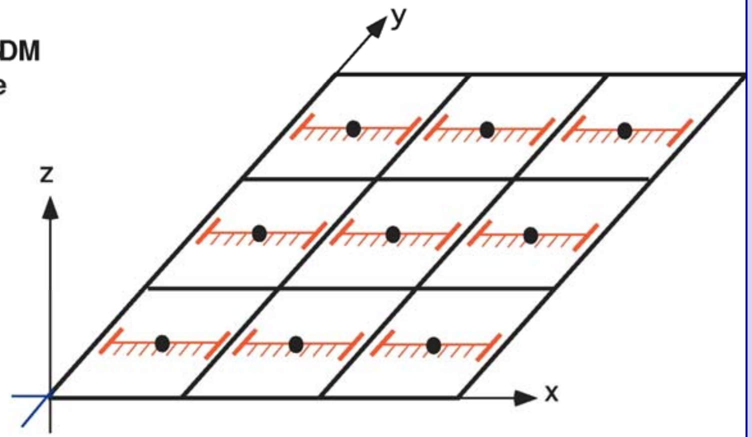


Cloud-Resolving Convection Parameterization or Super-Parameterization

Grabowski (2001), Khairoutdinov and Randall (2001)

Application of
a 2D CSRM within each column of a large-scale dynamical model (LSDM)
with periodic lateral boundary conditions

At the ● points, the LSDM and the domain-average of the CSRM interact.



Concept and viewgraph from Akio Arakawa

Pathway 2: Superparameterization

What do we get?

- ***Explicit deep convection***
- ***Explicit fractional cloudiness***
- ***Explicit cloud overlap and possible 3d cloud effects***
- ***Convectively generated gravity waves***

But…..

A GCM using a super-parameterization is three orders of magnitude more expensive than a GCM that uses conventional parameterizations.

On the other hand super-parameterizations provide a way to utilize more processors for a given GCM resolution

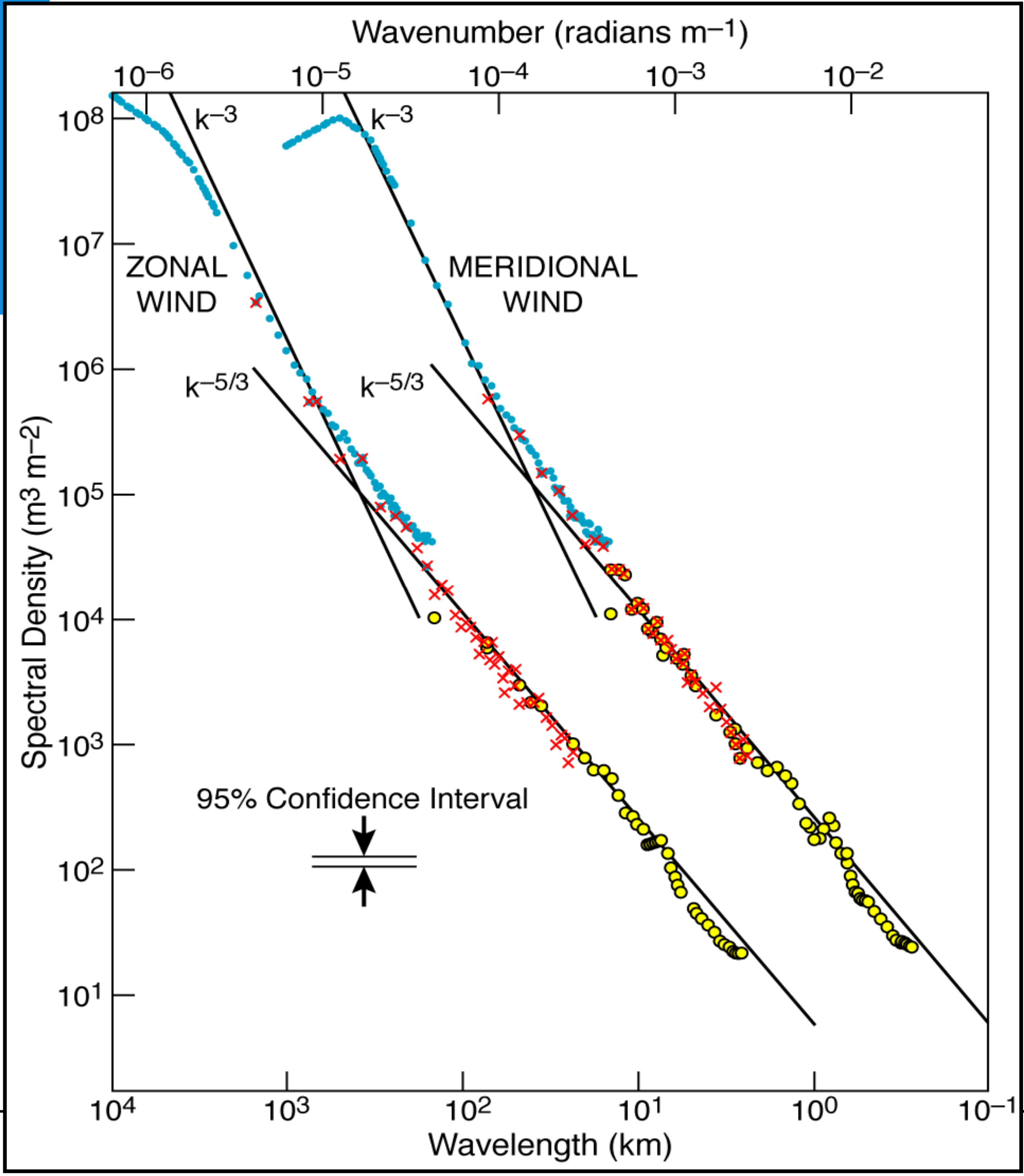
Boundary Layer Clouds, Microphysics and Turbulence still needs to be parameterized

2D?

5.

Scale Aware and Stochastic Parameterizations

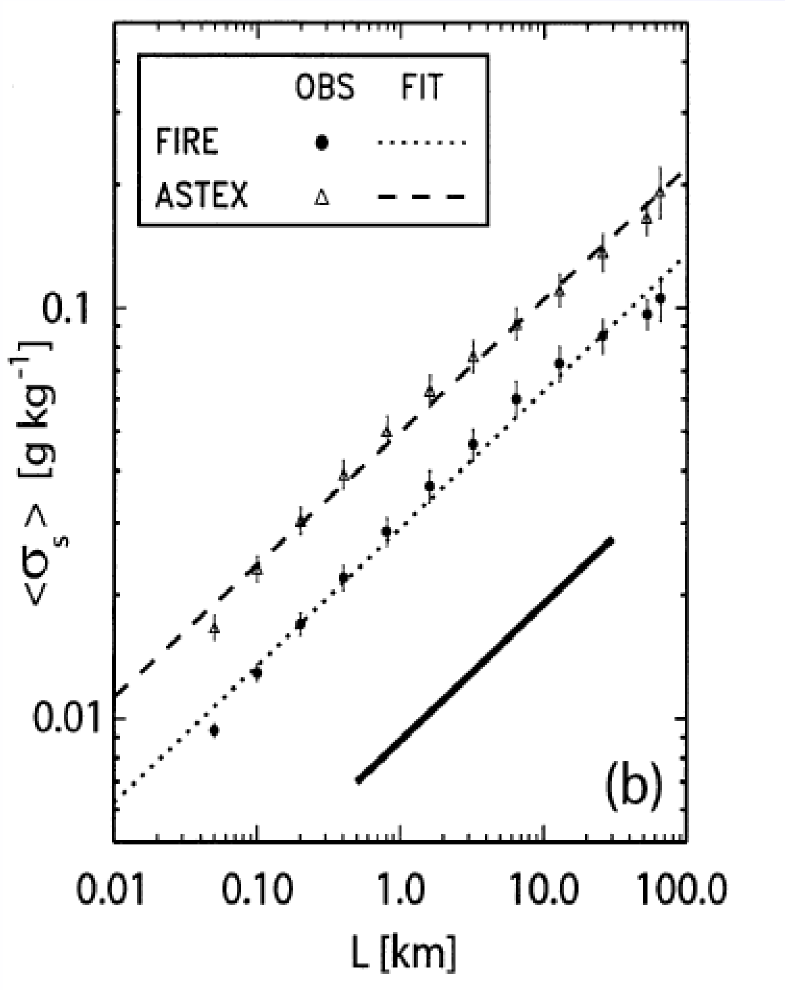
Kinetic energy spectra from aircraft



No Spectral Gap!!!

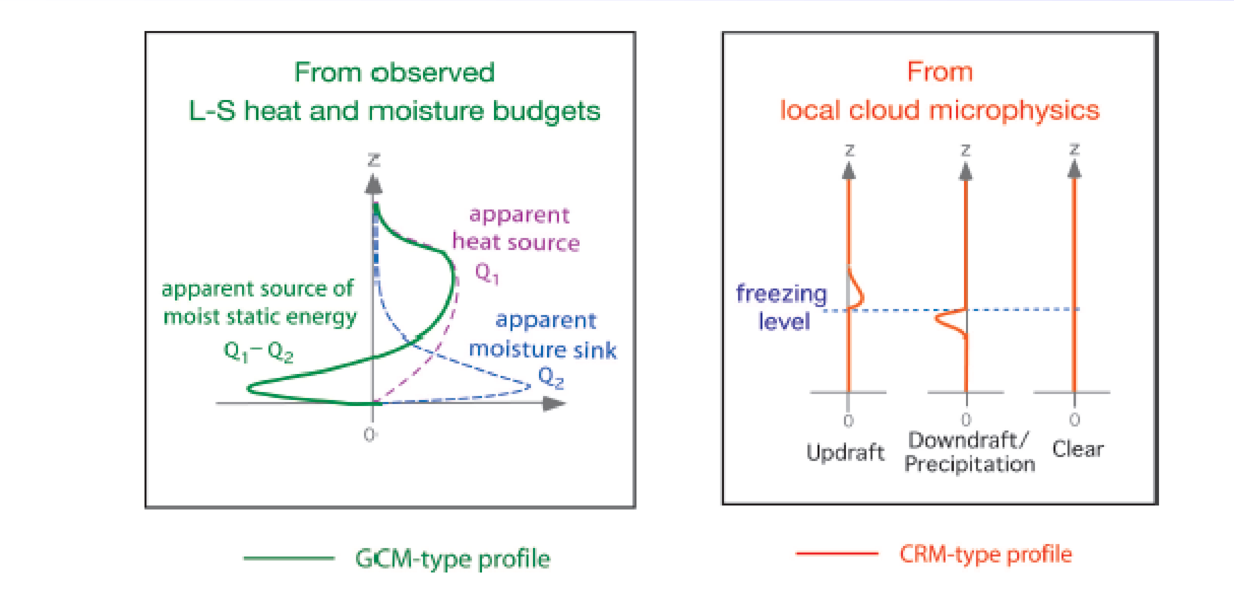
Nastrom and Gage, 1985

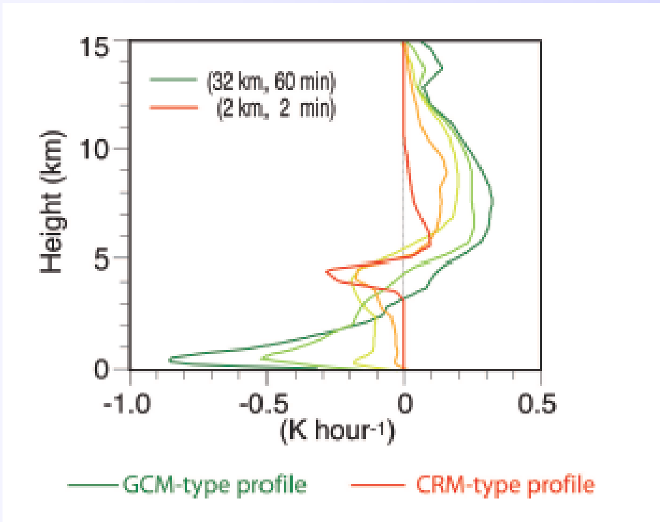
Similar for variance of temp and humidity



Cloud schemes: $\sigma_s = \sigma_s(l)$

Convection schemes: deep convection

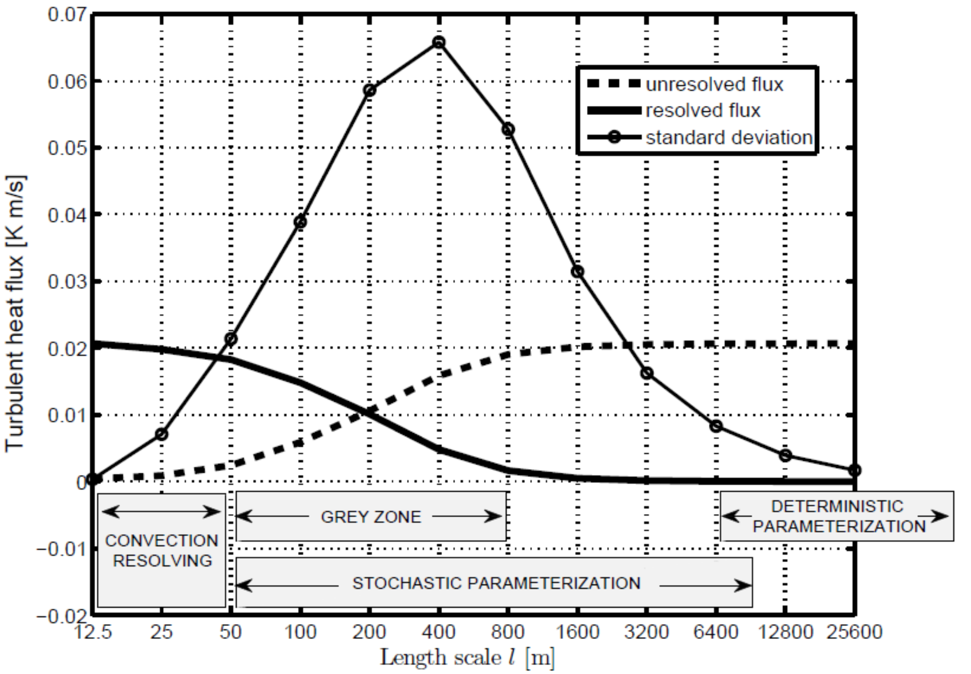


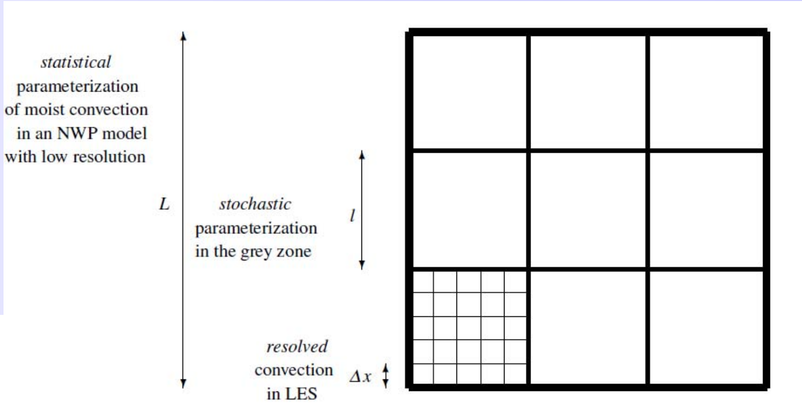


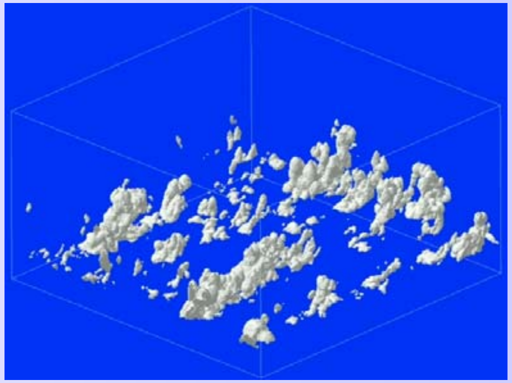
Arakawa 2011 ACP

Convection schemes: shallow convection

Dorrestijn, Siebesma, Crommelin, Jonker, 2012

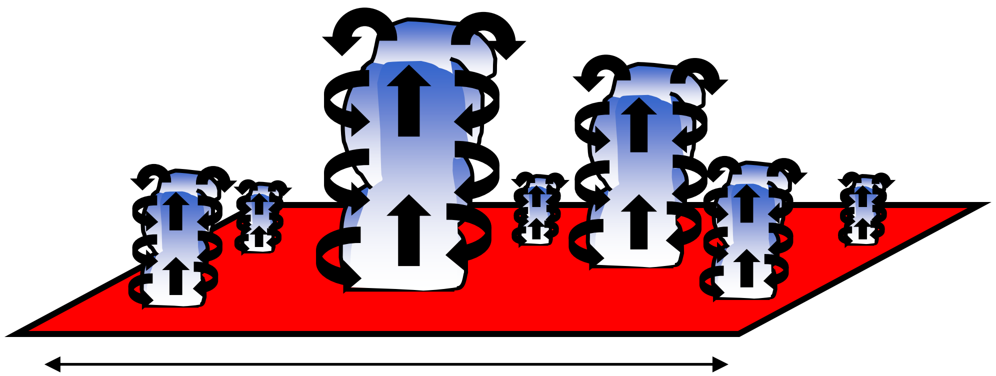






Deterministic versus Stochastic Convection (1)

- Traditionally convection parameterizations are deterministic:
  - Instantaneous grid-scale flow and mean state is taken as input and convective response is deterministic
  - One to one correspondency between sub-grid state and resolved state assumed.
  - Conceptually assumes that spatial average is a good proxy for the ensemble mean.
  - This assumption breaks down at higher resolutions

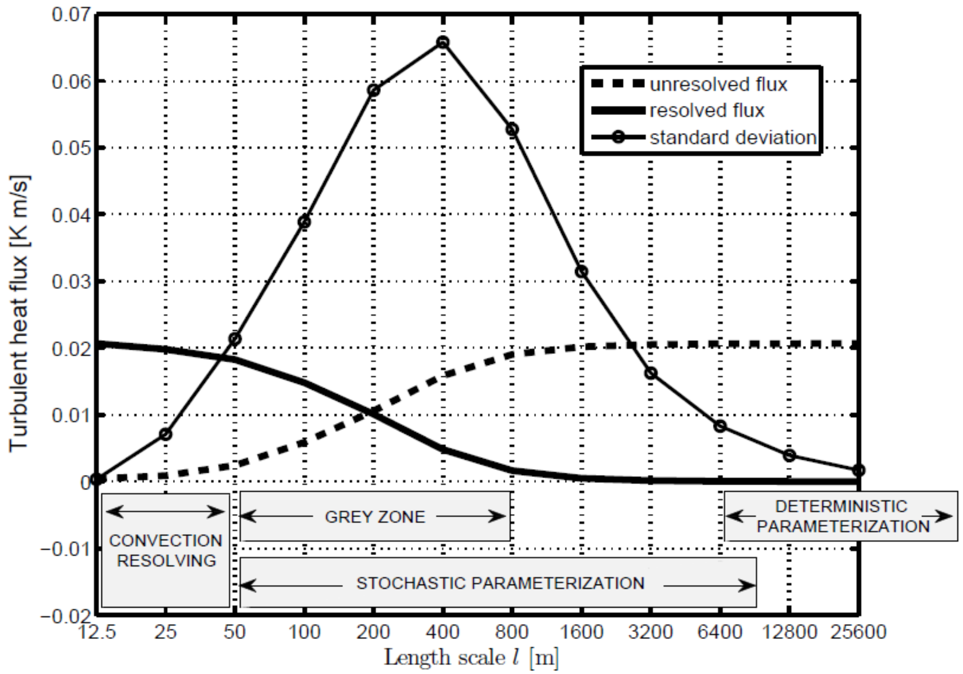


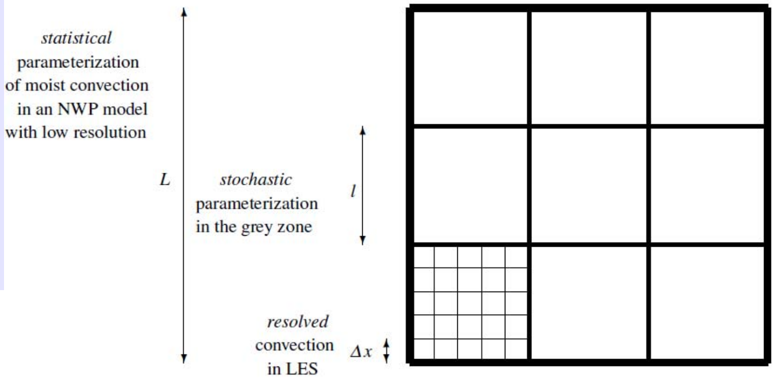
~500km

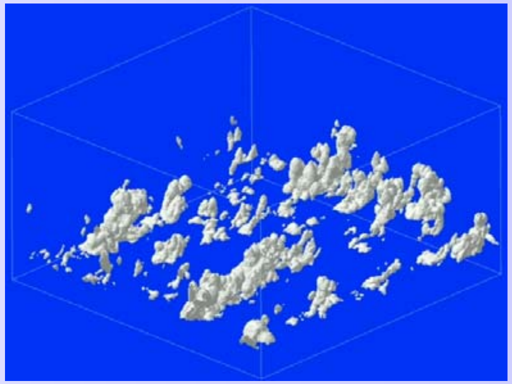
••••

Stochastic Noise happens especially in the Grey Zone

Dorrestijn, Siebesma, Crommelin, Jonker, 2012







All the new pathways are exciting and are happening now!

Parameterization is really about understanding cloud processes and their interaction with the large scale so: