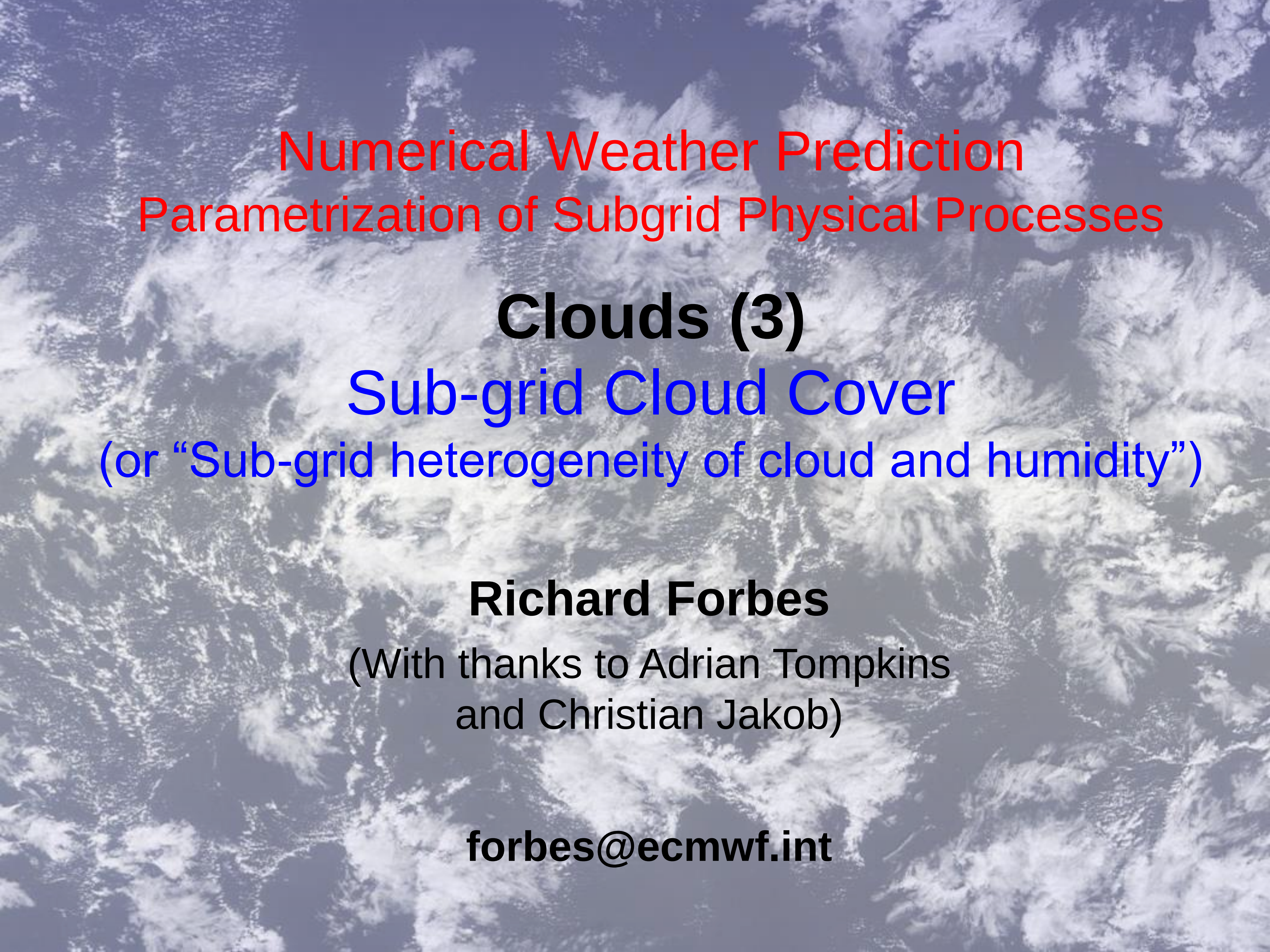


Numerical Weather Prediction
Parametrization of Subgrid Physical Processes

Clouds (3)
Sub-grid Cloud Cover
(or “Sub-grid heterogeneity of cloud and humidity”)

Richard Forbes

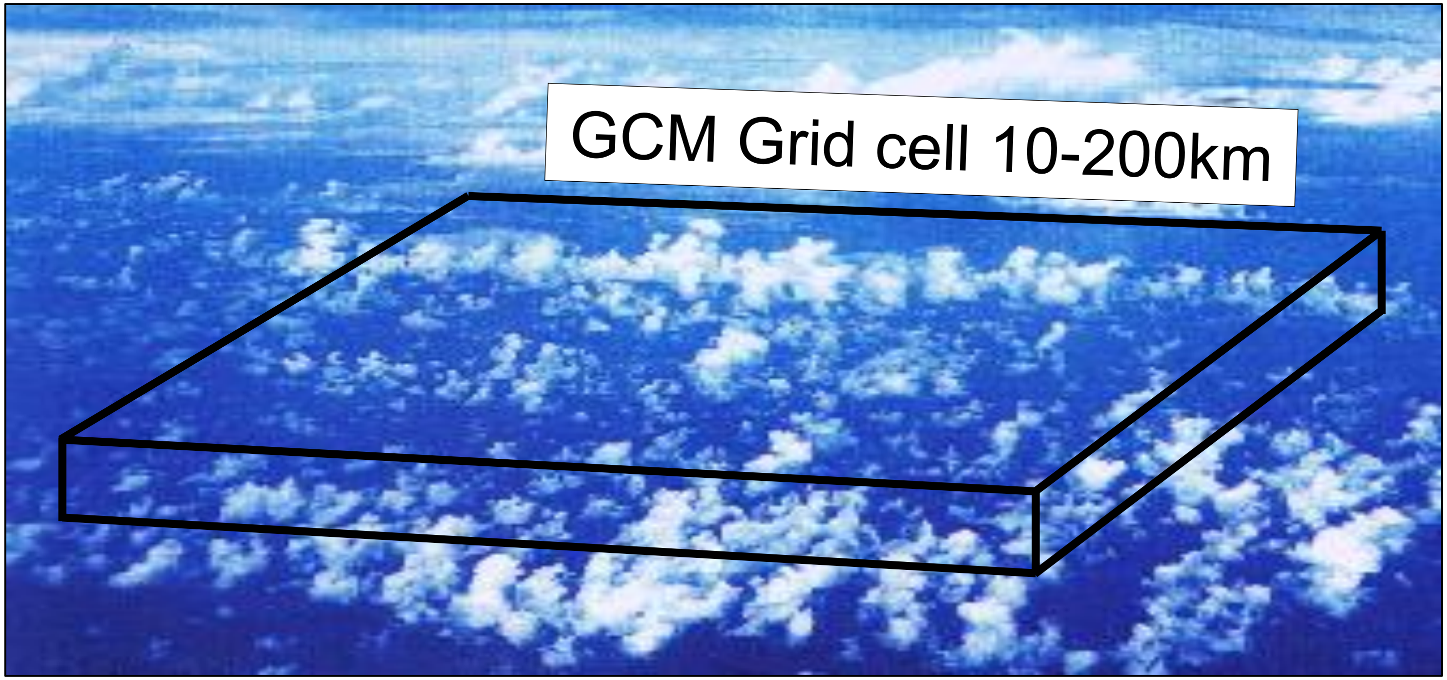
(With thanks to Adrian Tompkins
and Christian Jakob)

forbes@ecmwf.int

Clouds in GCMs:

Representing sub-grid heterogeneity

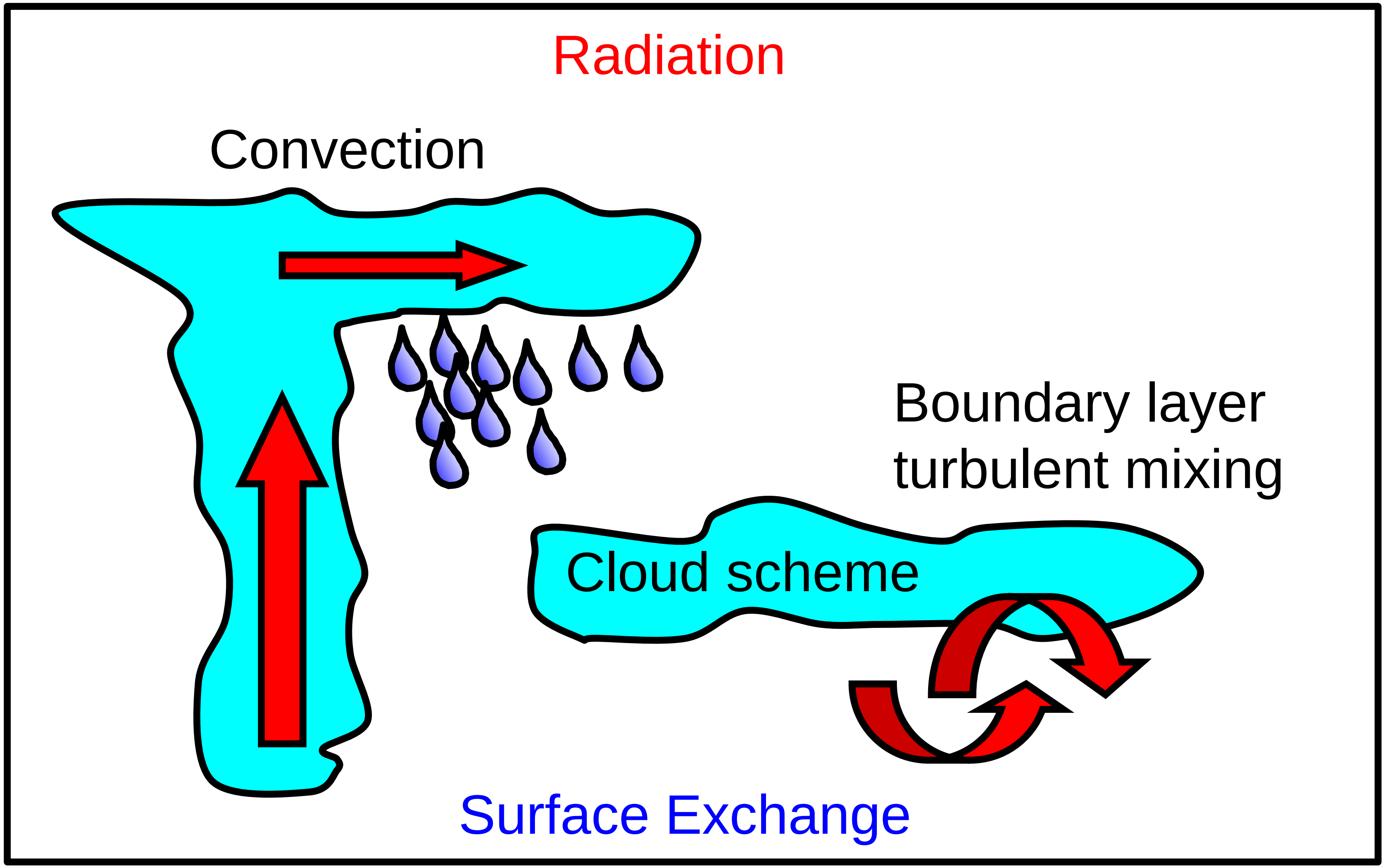
Many of the observed clouds and especially the processes within them are of subgrid-scale size (both horizontally and vertically)



Clouds in GCMs:

Representing sub-grid heterogeneity

Many heterogeneity assumptions across the model parametrizations…



Radiation

Convection

Boundary layer turbulent mixing

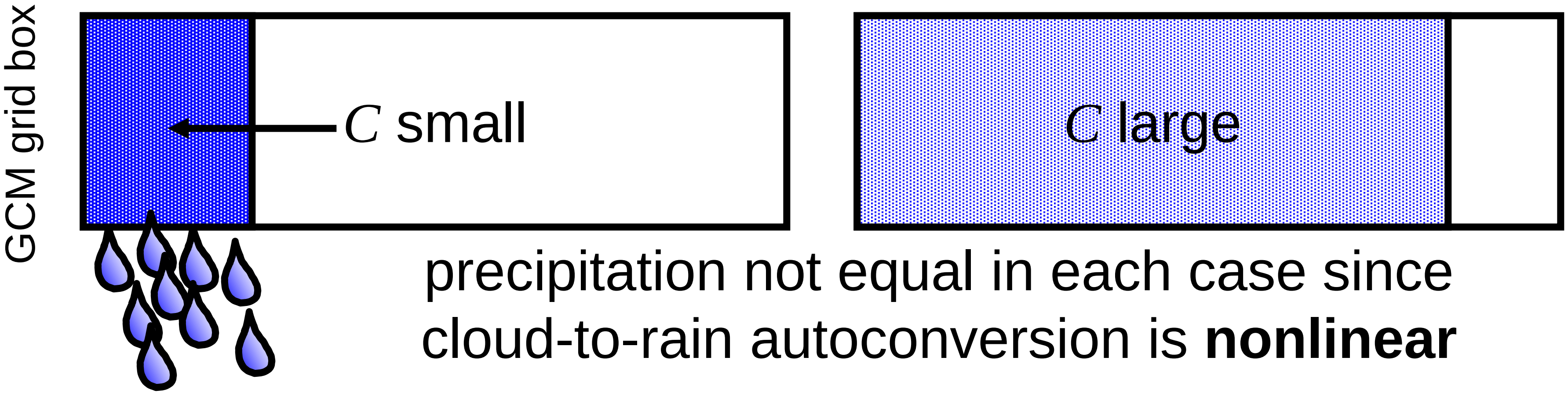
Cloud scheme

Surface Exchange

Why represent heterogeneity?

Important for microphysics

Imagine a cloud with condensate mass q_l and cloud fraction C
The in-cloud mass mixing ratio is q_l/C



precipitation not equal in each case since cloud-to-rain autoconversion is **nonlinear**

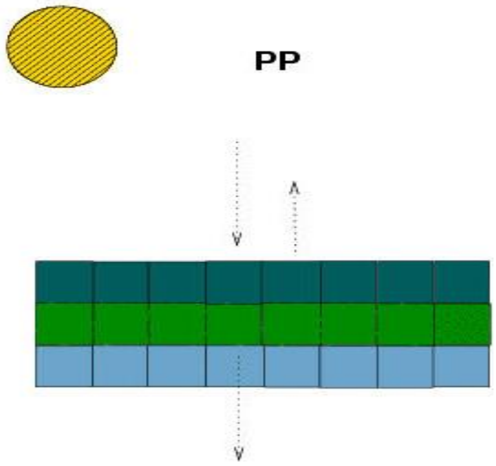
- Complex microphysics perhaps a wasted effort if assessment of cloud fraction C is poor!

- In addition, in-cloud condensate heterogeneity should also be represented, i.e. not all the cloud is precipitating?

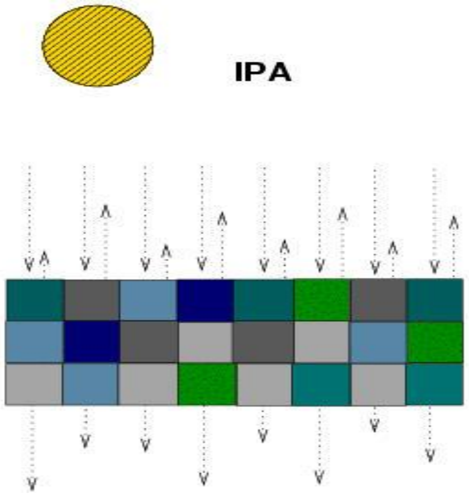
Why represent heterogeneity?

Important for radiation

- Assuming homogeneity can lead to biased radiative calculations (e.g. Cahalan et al. 1994, Barker et al 1996).
- Monte Carlo Independent Column Approximation, for example, can treat the inhomogeneity of in-cloud condensate and vertical overlap in a consistent way between the cloud and radiation schemes



Traditional approach (homogeneous)

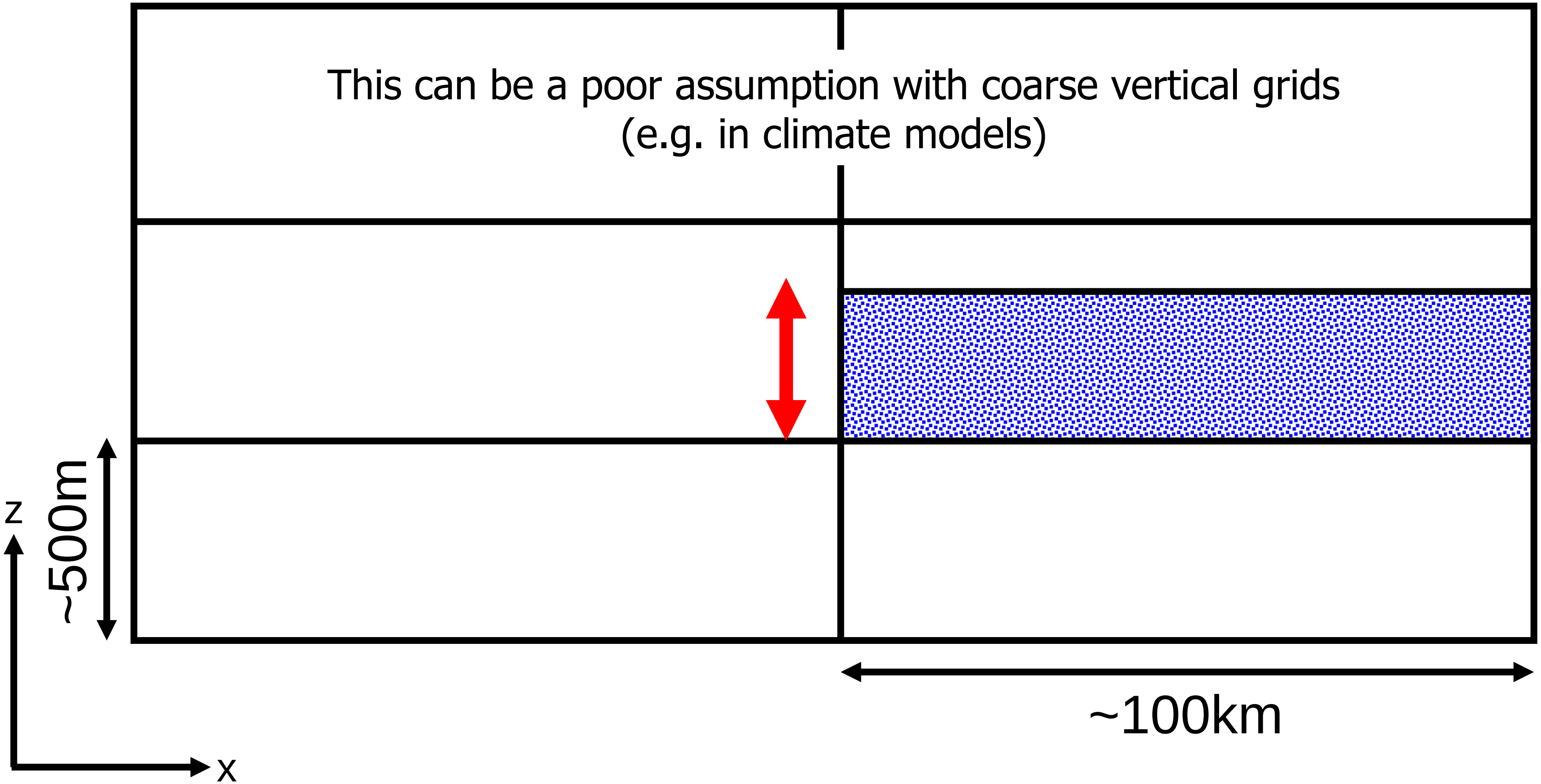


Independent Column Approximation, e.g. MCICA

Macroscale Issues of Parameterization

VERTICAL COVERAGE

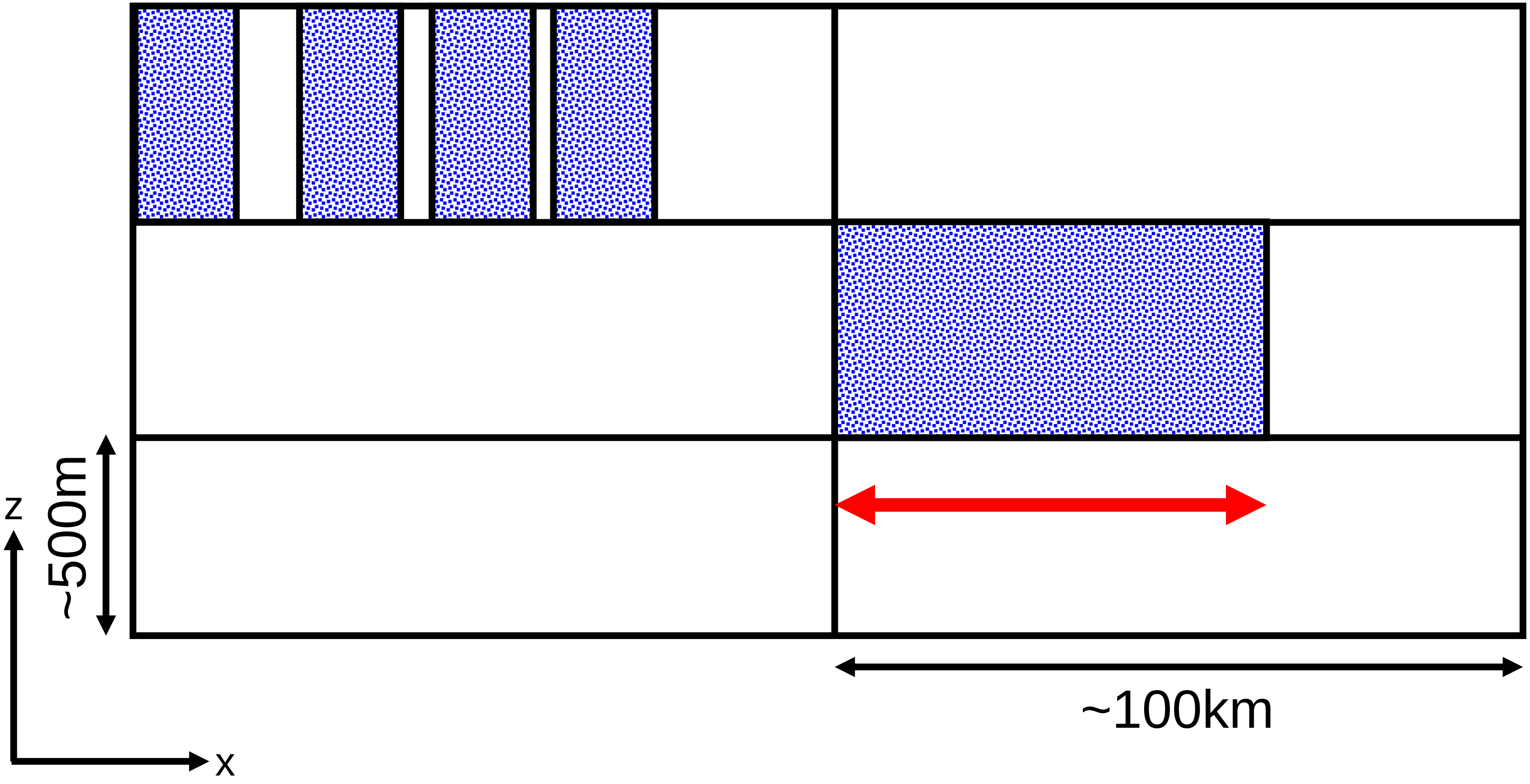
Most models assume that this is 1


This can be a poor assumption with coarse vertical grids
(e.g. in climate models)

Macroscale Issues of Parameterization

HORIZONTAL COVERAGE, *C*

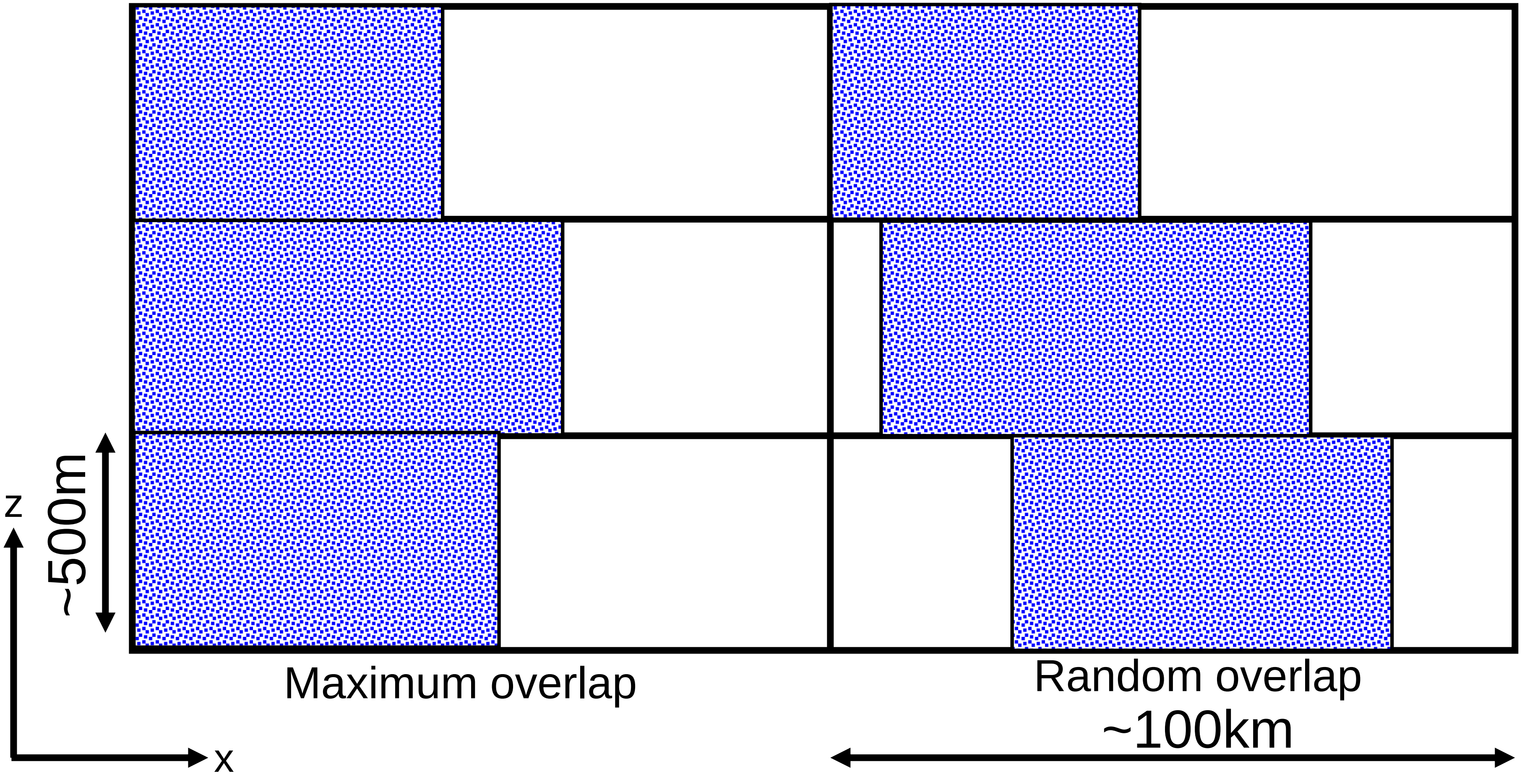
Spatial arrangement ?



Macroscale Issues of Parameterization

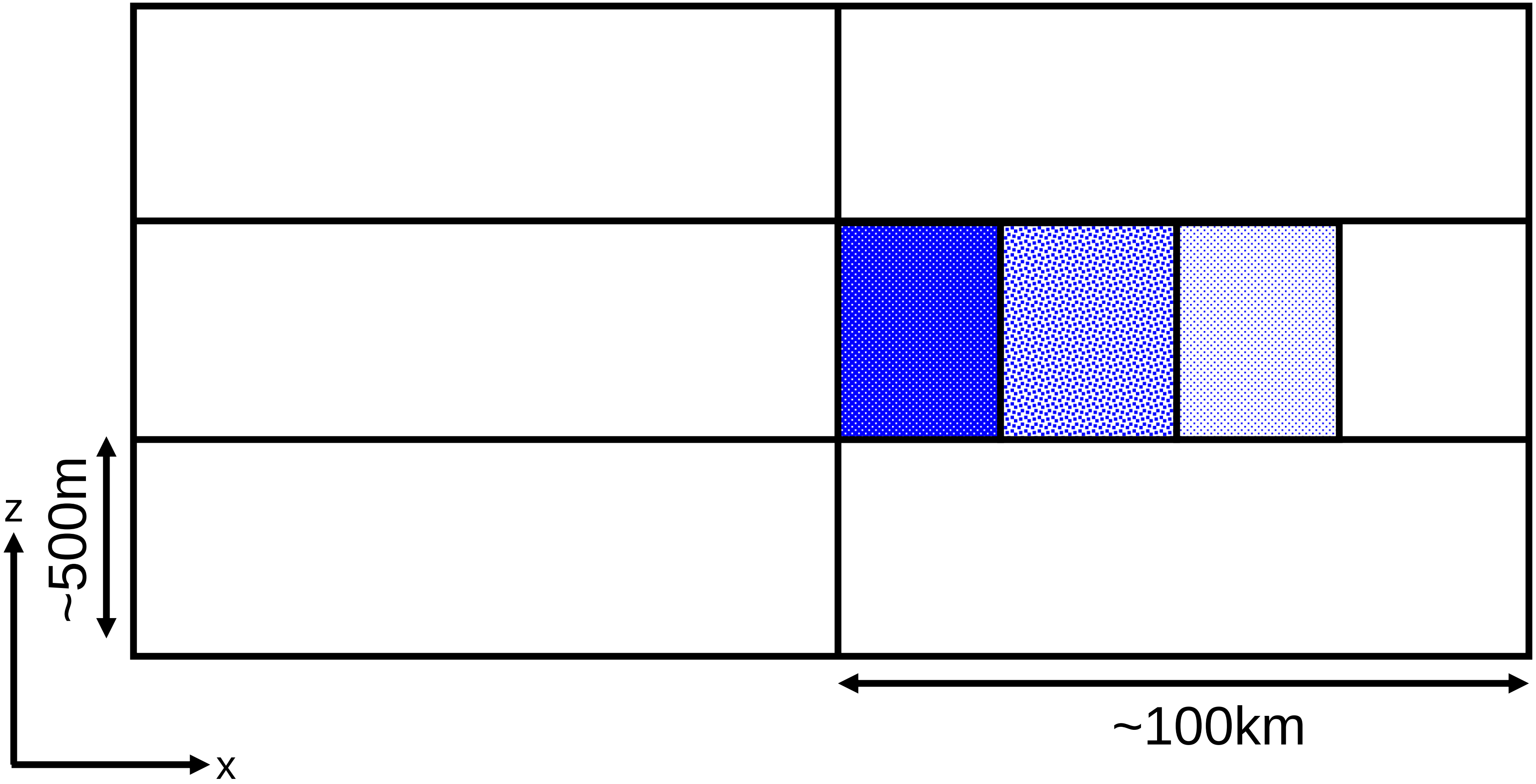
Vertical overlap of cloud

Important for radiation and microphysics interaction



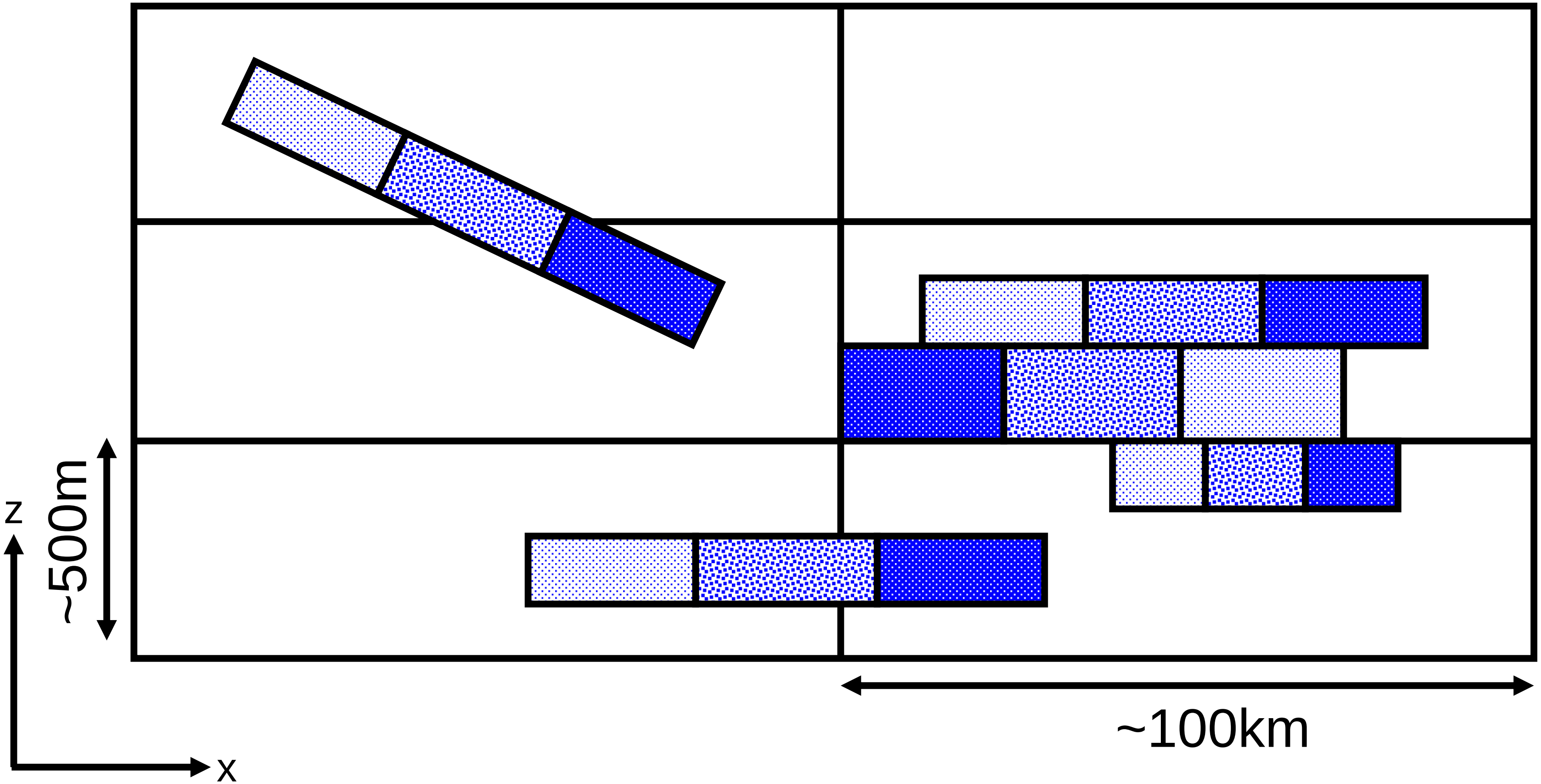
Macroscale Issues of Parameterization

In-cloud inhomogeneity
in terms of cloud water, particle size/number



Macroscale Issues of Parameterization

Just these issues can become very complex!!!



First: Some assumptions!

q_v = water vapour mixing ratio
q_c = cloud water (liquid/ice) mixing ratio
q_s = saturation mixing ratio = F(T,p)
q_t = total water (vapour+cloud) mixing ratio
RH = relative humidity = q_v / q_s

1. Local criterion for formation of cloud: $q_t > q_s$
   This assumes that no supersaturation can exist
2. Condensation process is fast (cf. GCM timestep)

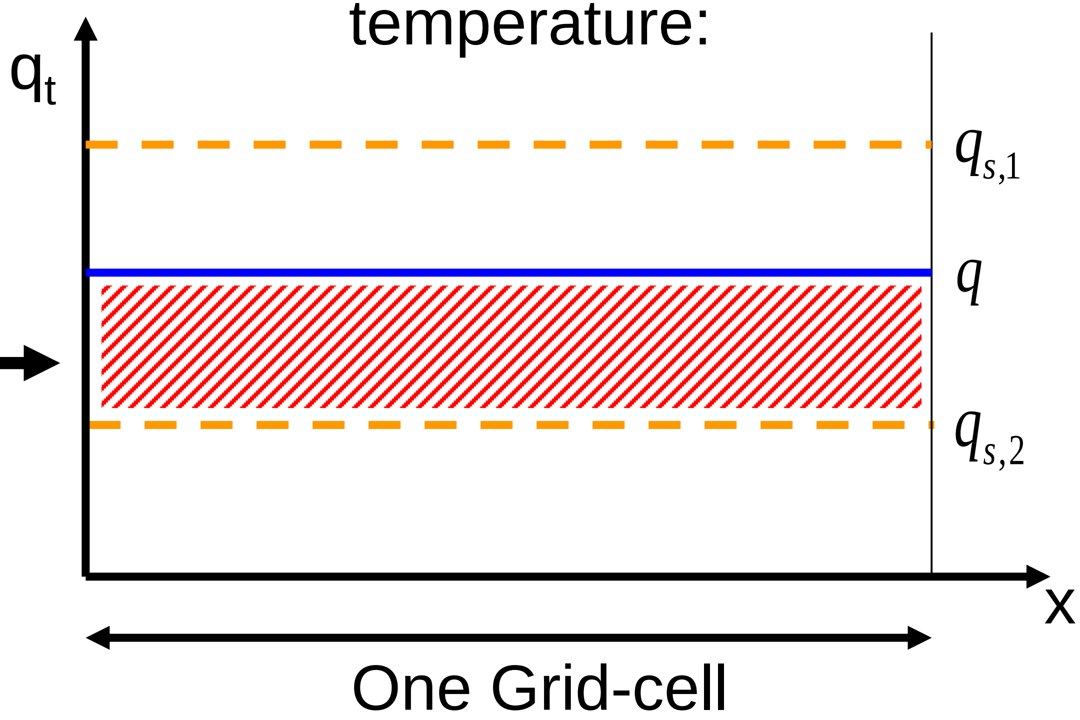
$$q_v = q_s \qquad q_c = q_t - q_s$$

!!Both of these assumptions less applicable in ice clouds!!

Partial cloud cover

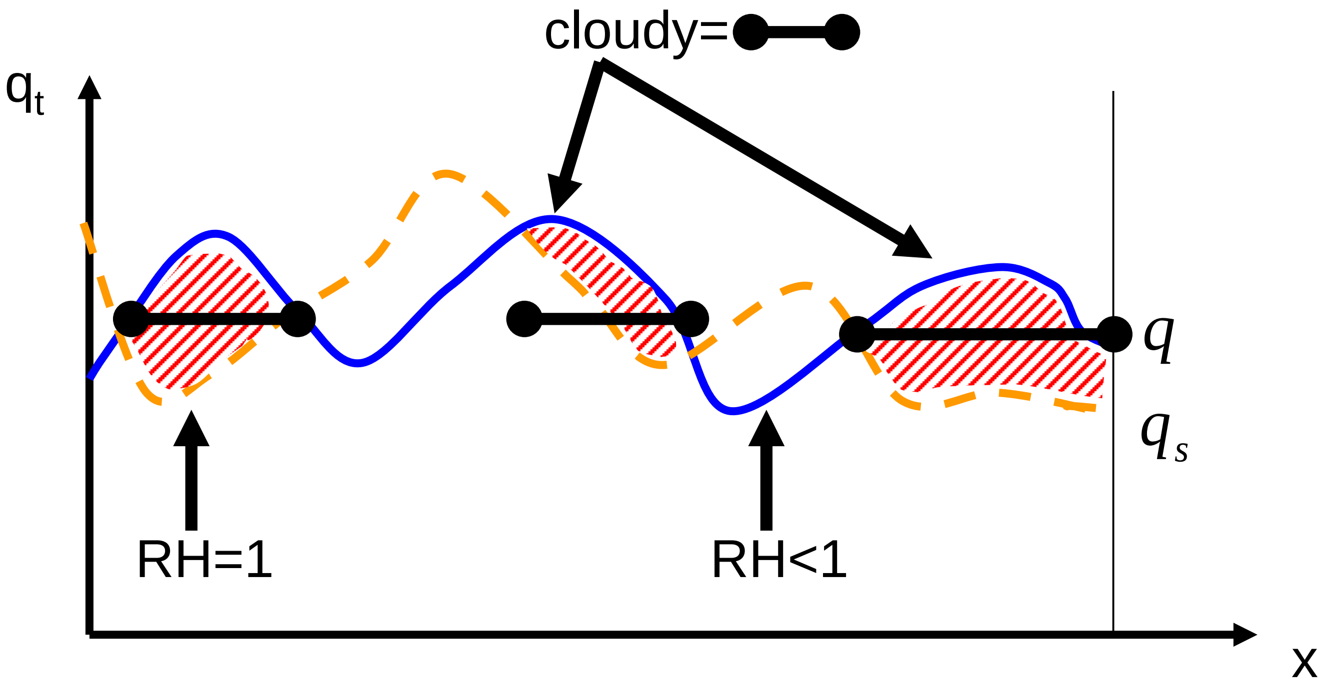
Homogeneous distribution of water vapour and temperature:

Note in the second case the relative humidity=1 from our assumptions



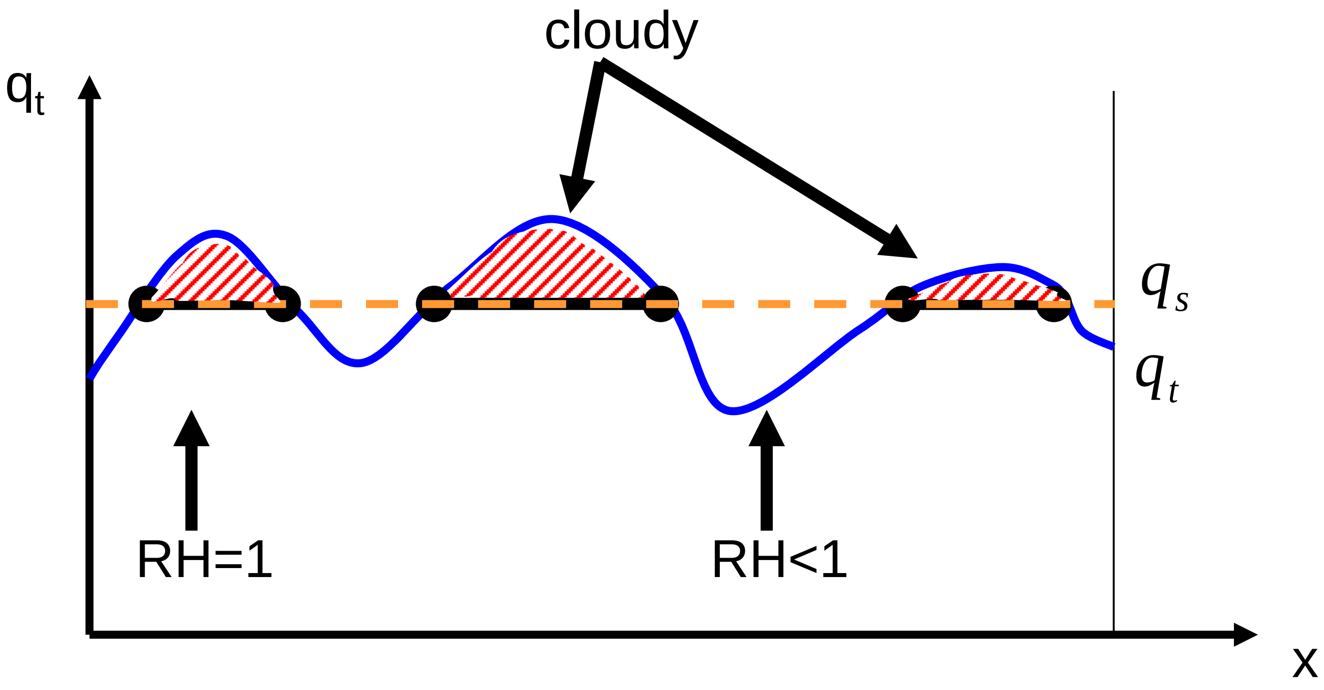
Partial coverage of a grid-box with clouds is only possible if there is an inhomogeneous distribution of temperature and/or humidity.

Heterogeneous Distribution of *T* and *q*



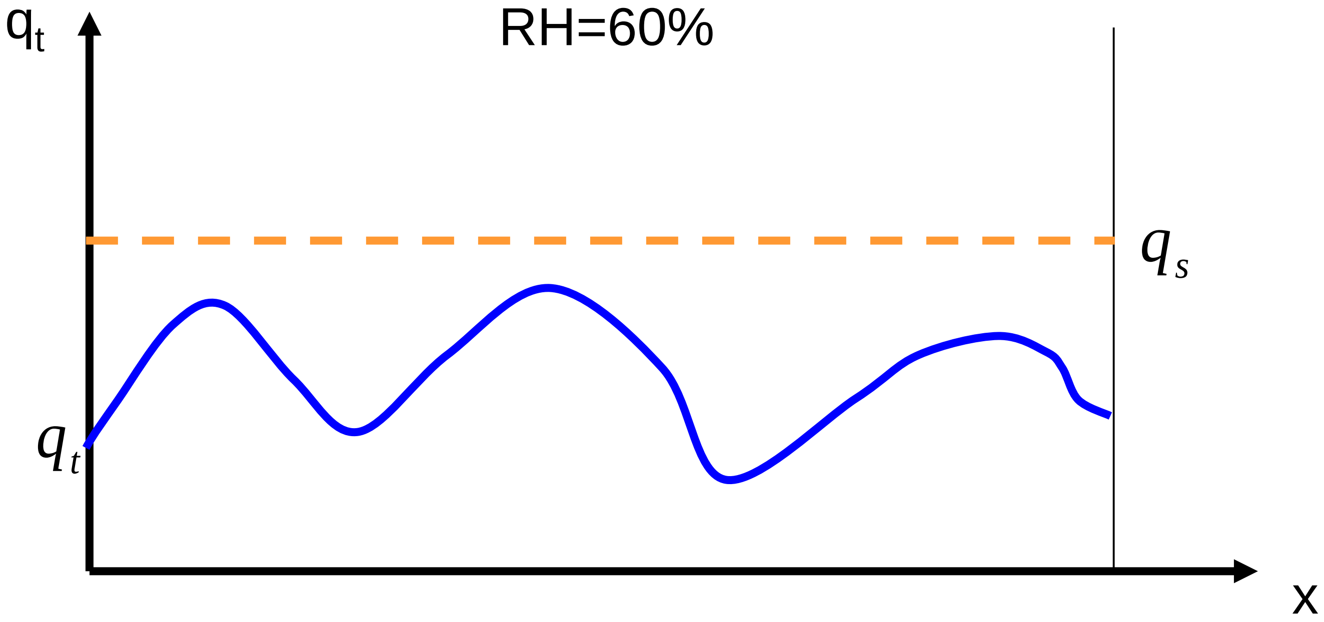
Another implication of the above is that clouds must exist before the grid-mean relative humidity reaches 1.

Heterogeneous Distribution of *q* only

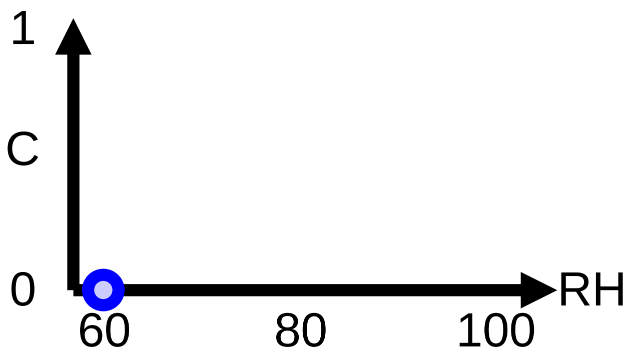


- The interpretation does not change much if we only consider humidity variability
- Throughout this talk I will neglect temperature variability
- Analysis of observations and model data indicates humidity fluctuations are more important most of the time.

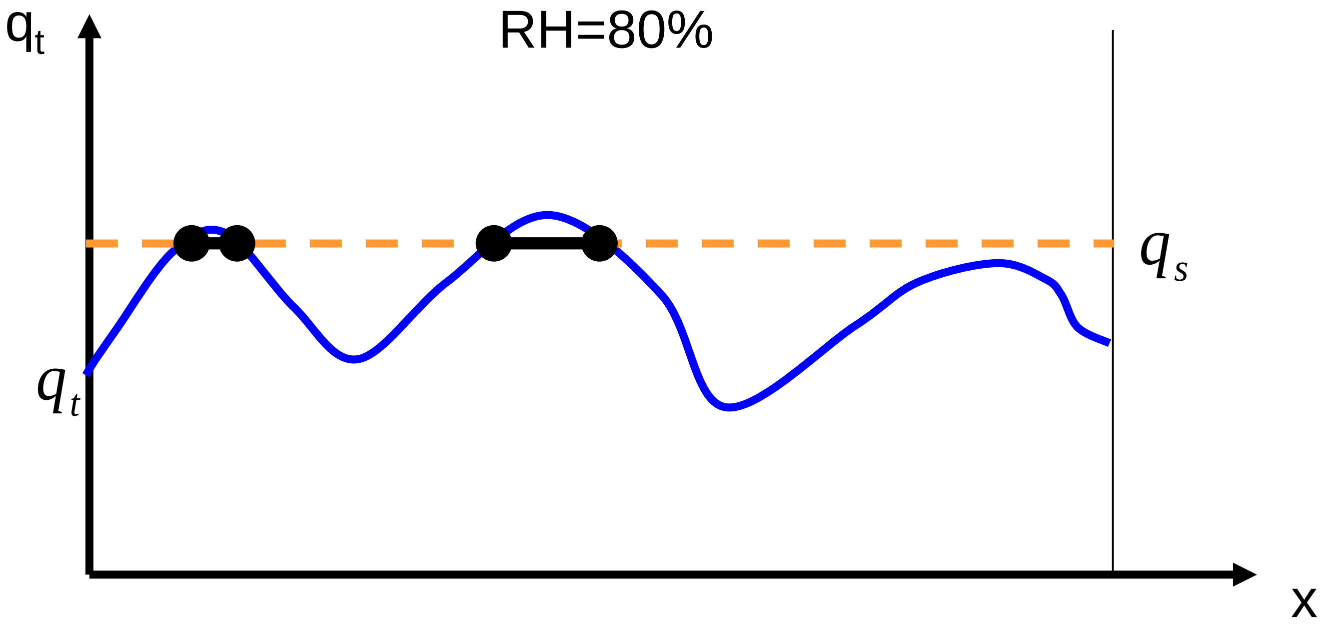
Simple Diagnostic Cloud Schemes:
Relative Humidity Schemes



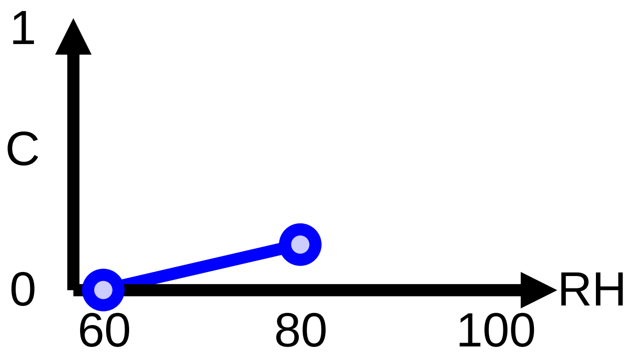
Take a grid cell with a certain (fixed) distribution of total water.
At low mean RH, the cloud cover is zero, since even the moistest part of the grid cell is subsaturated



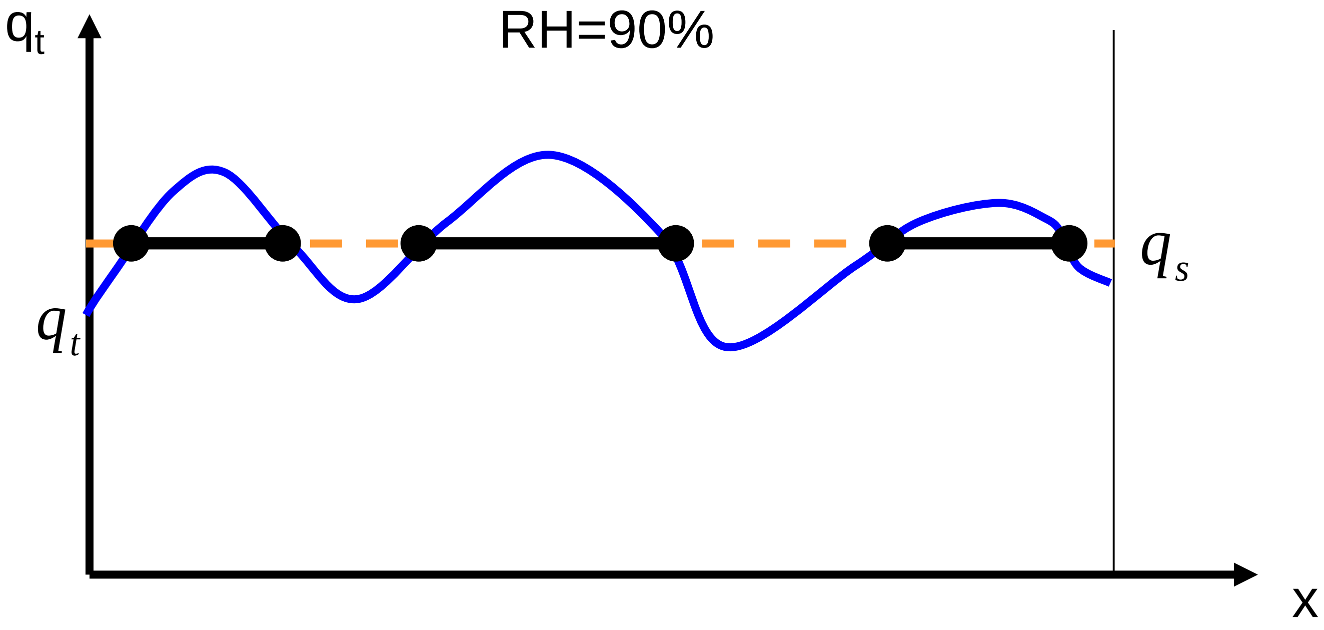
Simple Diagnostic Cloud Schemes:
Relative Humidity Schemes

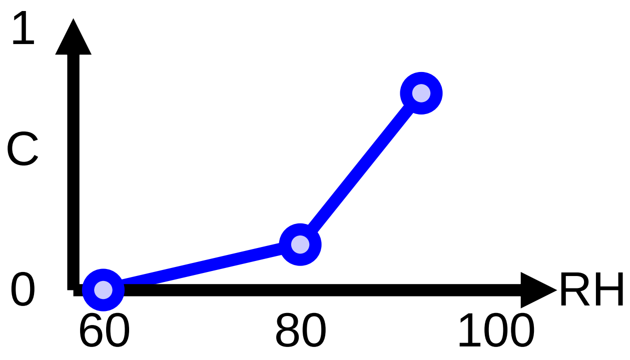


Add water vapour to the gridcell, the moistest part of the cell become saturated and cloud forms. The cloud cover is low.



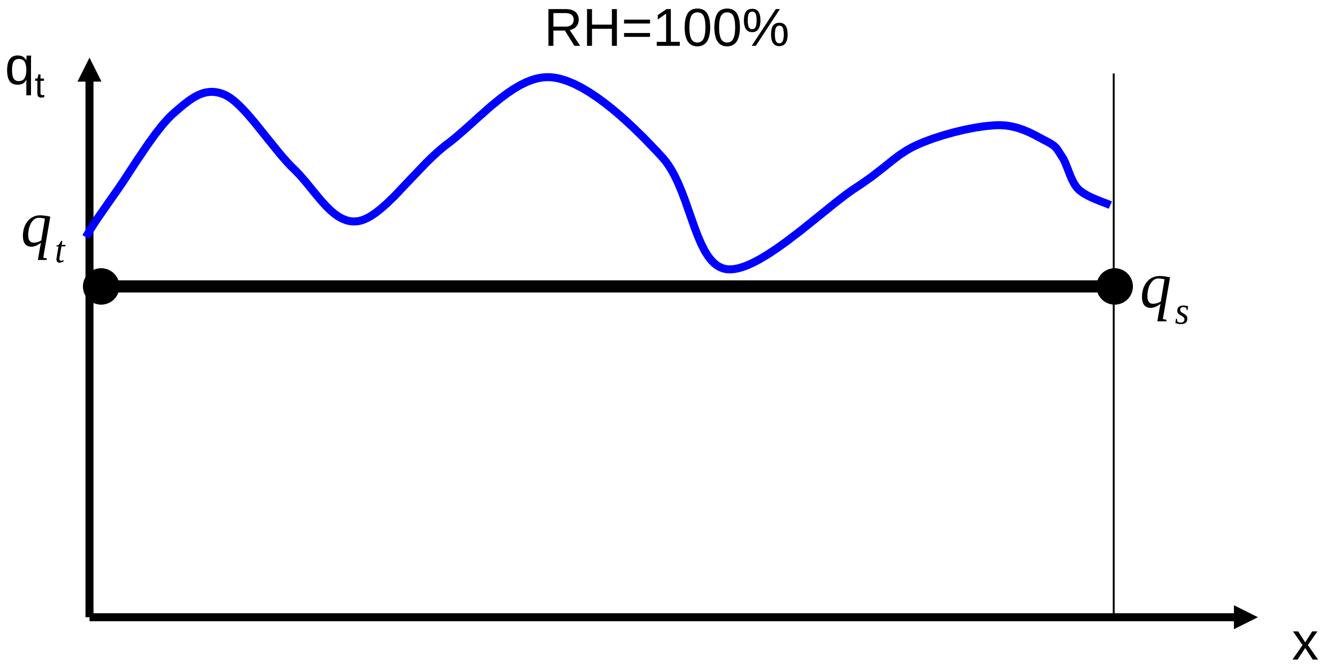
Simple Diagnostic Cloud Schemes:
Relative Humidity Schemes





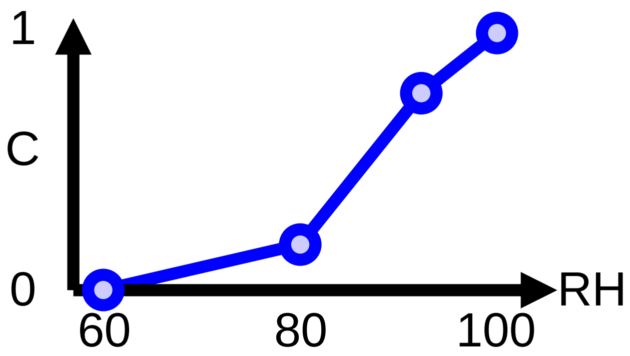
Further increases in RH
increase the cloud cover

Simple Diagnostic Cloud Schemes:
Relative Humidity Schemes



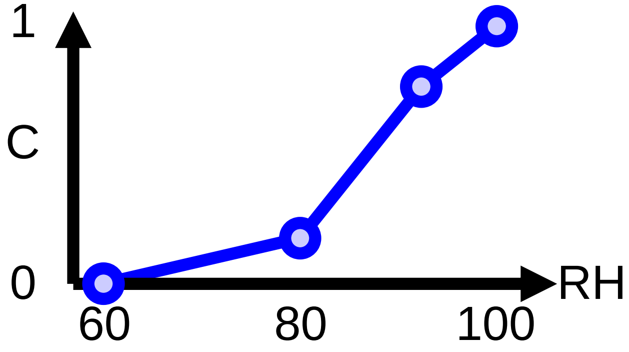
- The grid cell becomes overcast when RH=100%,due to lack of supersaturation

- Diagnostic RH-based parametrization C =f(RH)



Diagnostic Relative Humidity Schemes

- Many schemes, from the 1970s onwards, based cloud cover on the relative humidity (RH)
- e.g. Sundqvist et al. MWR 1989:



$$C = 1 - \sqrt{\frac{1 - RH}{1 - RH_{crit}}}$$

☺ Remember this for later!

RH_{crit} = critical relative humidity at which cloud assumed to form (= function of height, typical value is 60-80%)

Diagnostic Relative Humidity Schemes

- Since these schemes form cloud when RH<100%, they implicitly assume subgrid-scale variability for total water, q_t, (and/or temperature, T).

- However, the actual PDF (the shape) for these quantities and their variance (width) are often not known.

- They are of the form: “*Given a RH of X% in nature, the mean distribution of* q_t *is such that, on average, we expect a cloud cover of Y%*”.

Diagnostic Relative Humidity Schemes

- Advantages:
  - – Better than homogeneous assumption, since clouds can form before grids reach saturation.
- Disadvantages:
  - – Cloud cover not well coupled to other processes.
  - – In reality, different cloud types with different coverage can exist with same relative humidity. This can not be represented.
- Can we do better?

Diagnostic Relative Humidity Schemes

- Could add further predictors…
  - e.g. Xu and Randall (1996) sampled cloud scenes from a 2D cloud resolving model to derive an empirical relationship with two predictors, relative humidity AND cloud condensate:

$$\boxed{C = F(RH, q_c)}$$

  - e.g. scheme operational at ECMWF until 1995 (Slingo) adds dependence on vertical velocities, ω, as well as RH for different cloud types:

$$C_m = \begin{cases} 0 & \omega \geq 0 \\ C_m^{*}\, \omega / \omega_{crit} & \omega_{crit} \leq \omega < 0 \\ C_m^{*} & \omega < \omega_{crit} \end{cases}$$

$$C_m^{*} = \left[\max\left(\frac{RH - RH_{crit}}{1 - RH_{crit}}, 0 \right) \right]^2$$

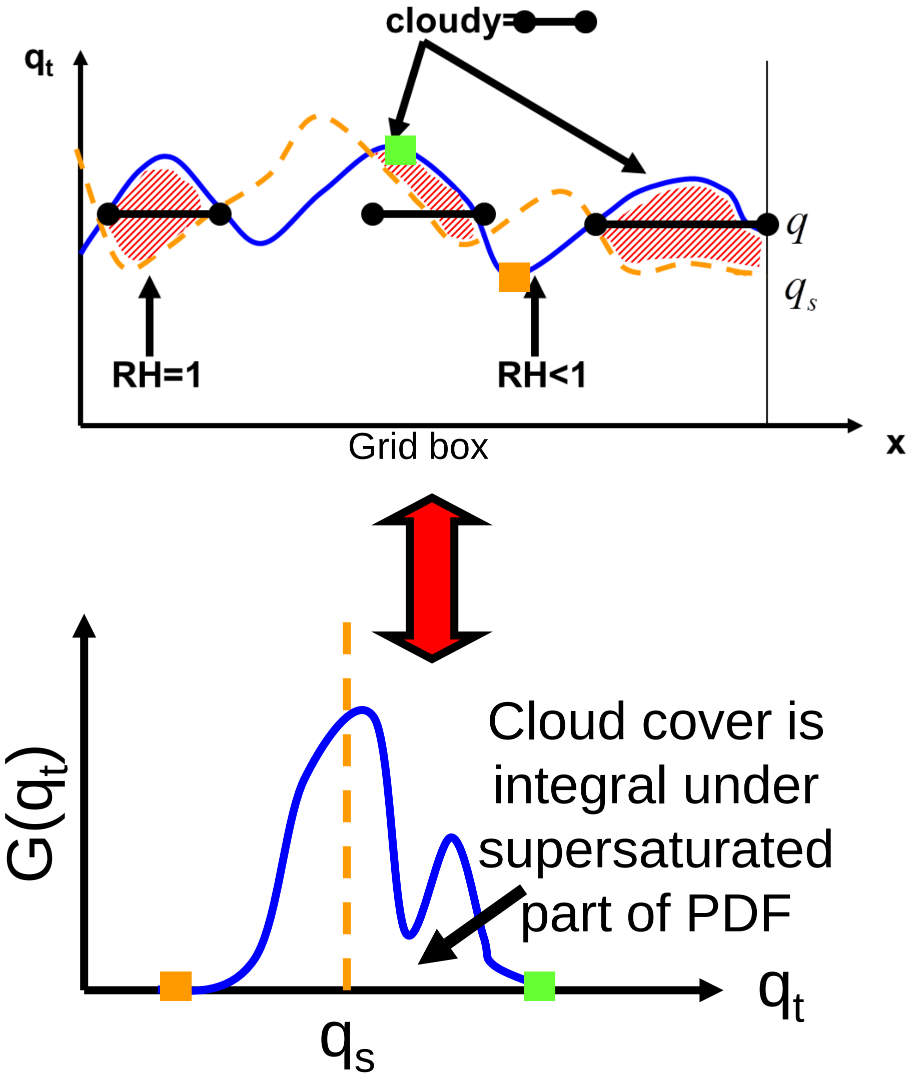
- More predictors, more degrees of freedom = flexible
- But still do not know the form of the PDF (is cloud resolving model valid? Is it representative for all situations?)
- Can we do better?

Statistical PDF Schemes

- Statistical schemes explicitly specify the probability density function (PDF), *G*, for the total water q_t (and sometimes also temperature)

$$C = \int_{q_s}^{\infty} G(q_t)\,dq_t$$

$$q_c = \int_{q_s}^{\infty} (q_t - q_s)\,G(q_t)\,dq_t$$



Cloud cover is integral under supersaturated part of PDF

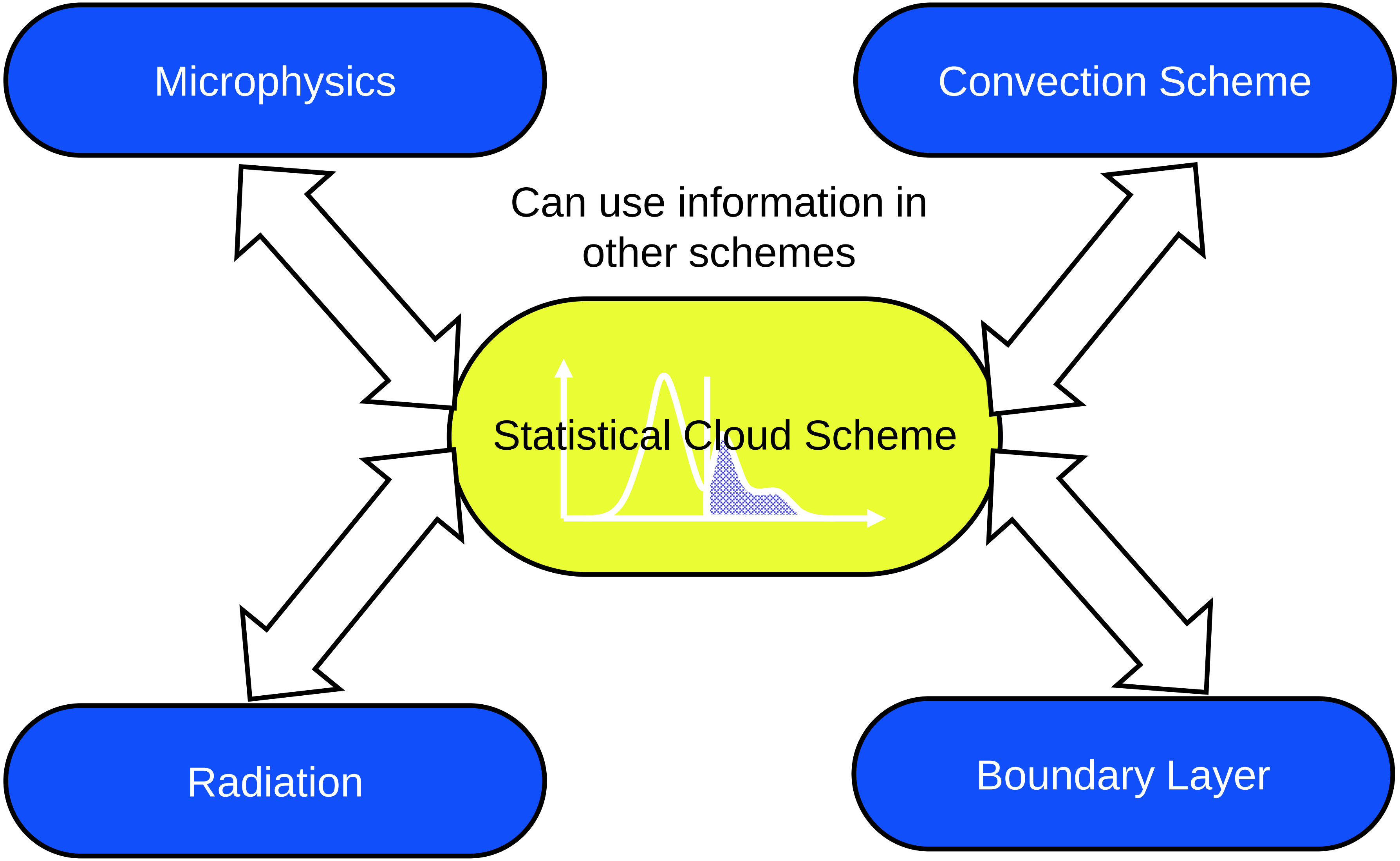
Sommeria and Deardorff (1977), Mellor (1977)

Statistical PDF Schemes

- Knowing the PDF has advantages:
  - Information concerning subgrid fluctuations of humidity and cloud condensate is available (for all parametrizations) , e.g.
    - More accurate calculation of radiative fluxes
    - Unbiased calculation of microphysical processes
  - Use of underlying PDF means cloud variables (condensate, cloud fraction) are always self-consistent.
  - Physically-based. Can evaluate with observations.

(Note, location of clouds within grid cell is still not known)

Statistical PDF scheme:
Consistency across parametrizations



Microphysics

Convection Scheme

Can use information in
other schemes

Statistical Cloud Scheme

Radiation

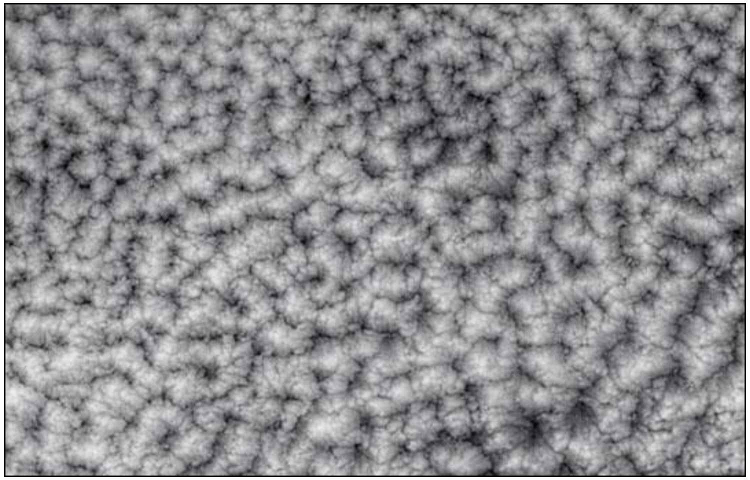
Boundary Layer

Building a statistical cloud scheme

What do we observe?

- Limited observations to determine q_t PDF
  - Aircraft data
    - limited coverage
  - Tethered balloon
    - boundary layer only
  - Satellite
    - difficulties resolving in vertical
    - no q_t observations
    - poor horizontal resolution
  - Ground-based radar/Raman Lidar
    - one location

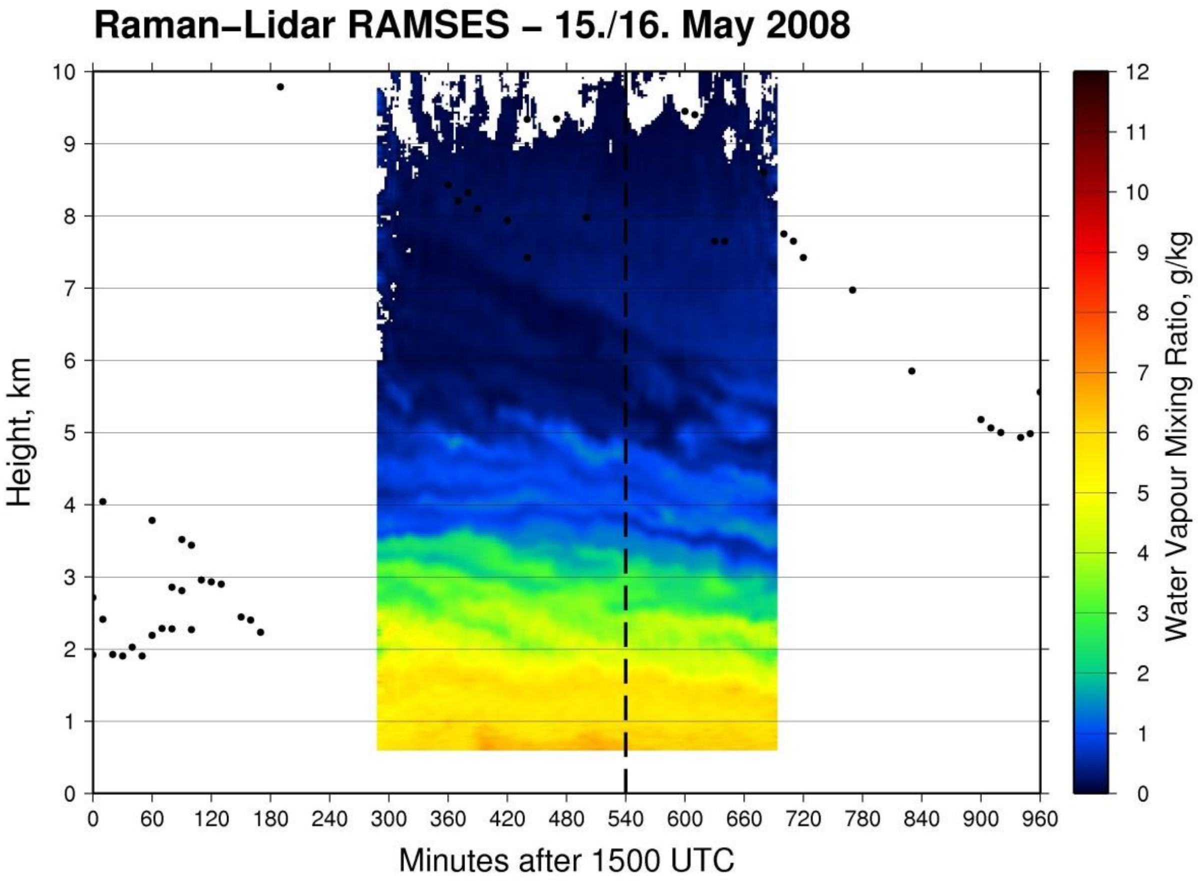
Modis image from NASA website

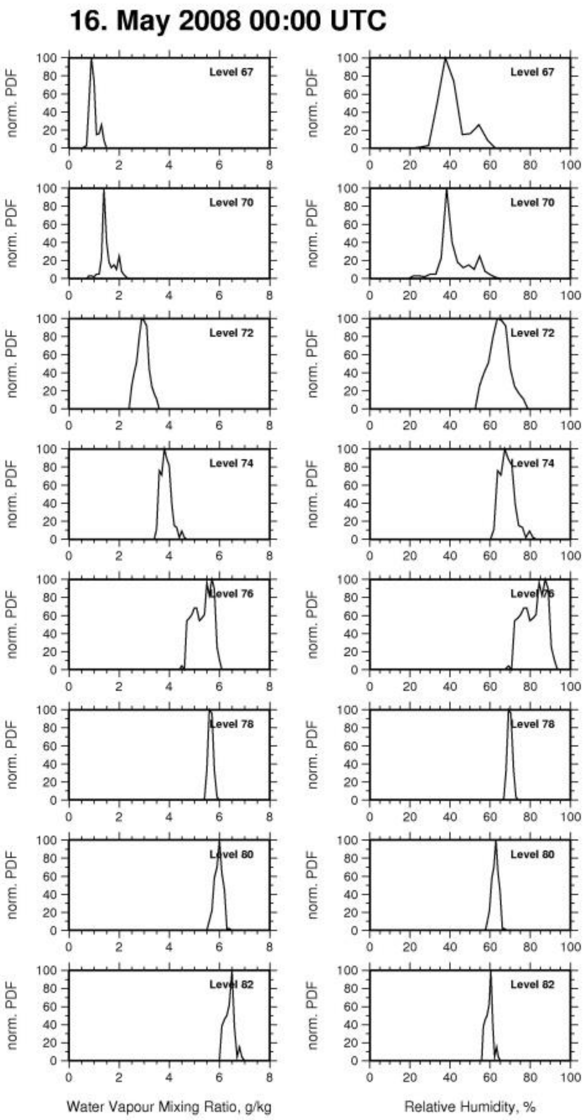


- Cloud Resolving models have also been used
    - realism of microphysical parametrization?

Building a statistical cloud scheme

Observed PDF of water vapour/RH Raman Lidar





From Franz Berger

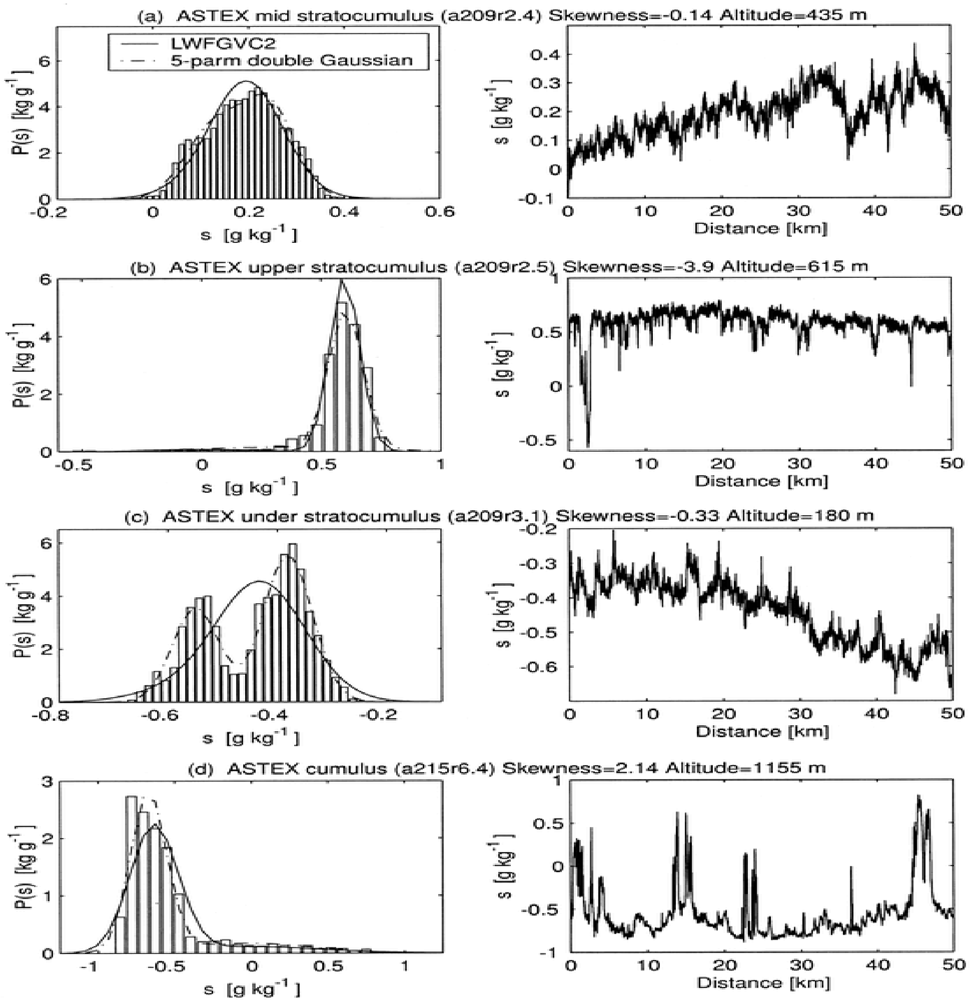
Building a statistical cloud scheme

Observed PDF example from aircraft

Example, aircraft data from Larson et al. 01/02

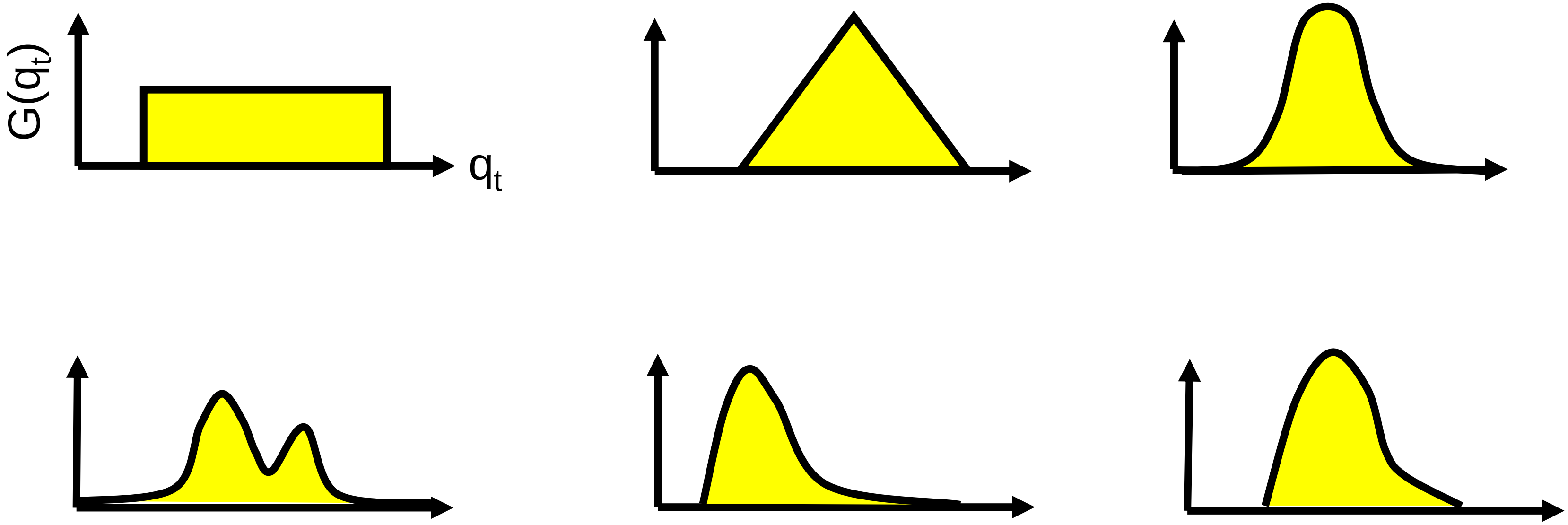
PDFs are mostly approximated by uni or bi-modal distributions, describable by a few parameters

PDF Data



Building a statistical cloud scheme
Functional form

- Need to represent with a functional form, specify the:
  - (1) PDF shape (unimodal, bimodal, symmetrical, bounded?)
  - (2) PDF moments (mean, variance, skewness?)
  - (3) Diagnostic or prognostic (how many degrees of freedom?)

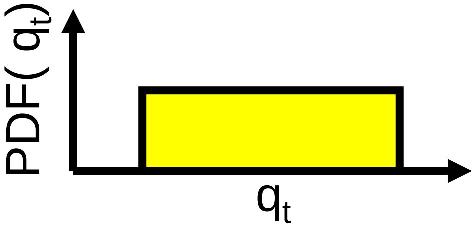


Building a statistical cloud scheme

(1) Specification of PDF shape

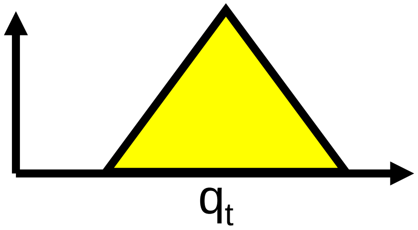
Many function forms have been used

symmetrical distributions:



Uniform:

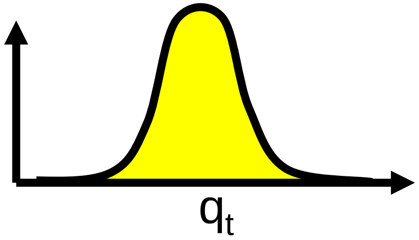
Letreut and Li (91)



Triangular:

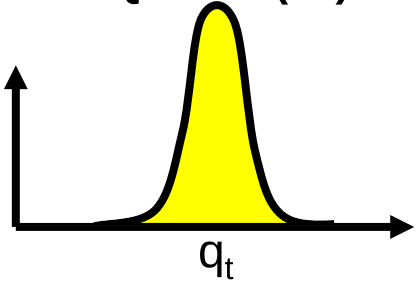
Smith QJRMS (90)

Bounded



Gaussian:

Mellor JAS (77)



s^4 polynomial:

Lohmann et al. J. Clim (99)

Unbounded:

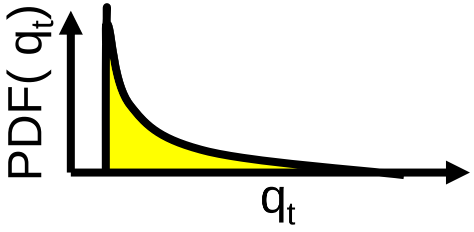
Can clip, but need additional parameters

Building a statistical cloud scheme

(1) Specification of PDF shape

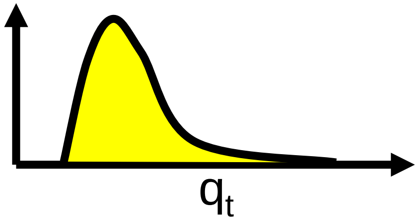
skewed distributions:

Unbounded,
always skewed



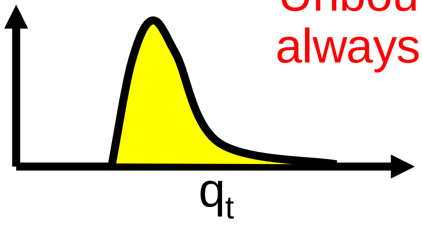
Exponential:

Sommeria and Deardorff JAS (77)



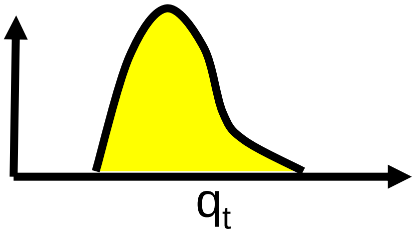
Lognormal:

Bony & Emanuel JAS (01)



Gamma:

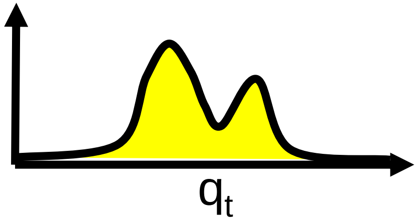
Barker et al. JAS (96)



Beta:

Tompkins JAS (02)

Bounded, symmetrical or skewed

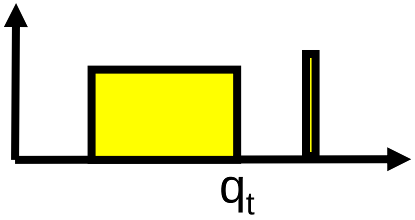


Double Gaussian:

Lewellen and Yoh JAS (93),

Golaz et al. JAS 2002

(CLUBB)



Uniform-delta:

Tiedtke (1993)

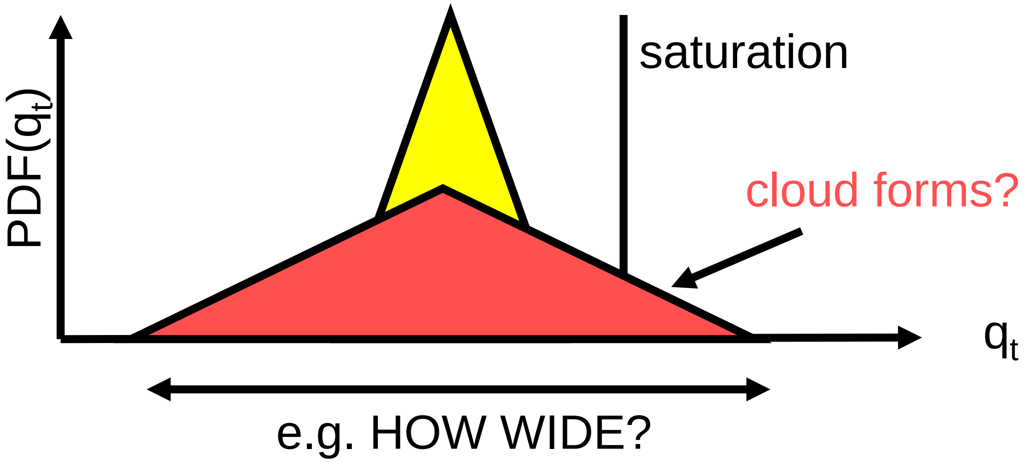
(ECMWF)

Building a statistical cloud scheme

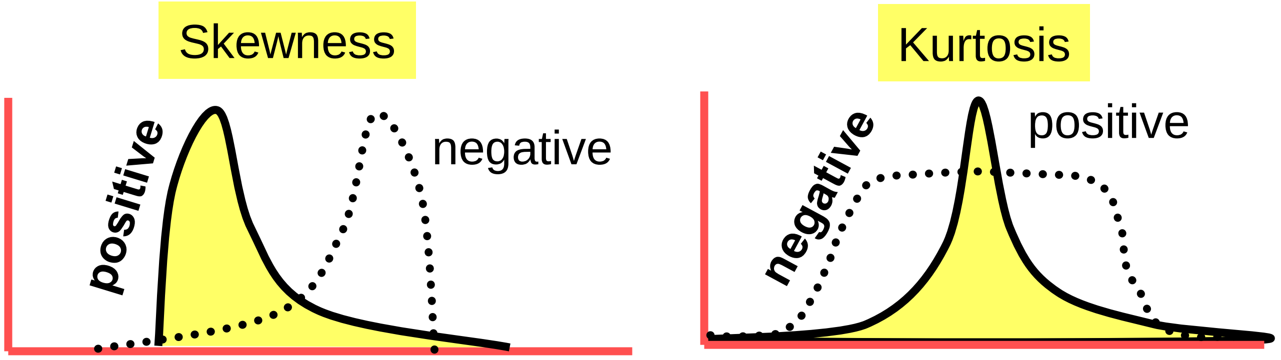
(2) Specification of PDF moments

Need also to determine the moments of the distribution:

- Variance (Symmetrical PDFs)
- Skewness (Higher order PDFs)
- Kurtosis (4-parameter PDFs)



Moment 1=MEAN
Moment 2=VARIANCE
Moment 3=SKEWNESS
Moment 4=KURTOSIS

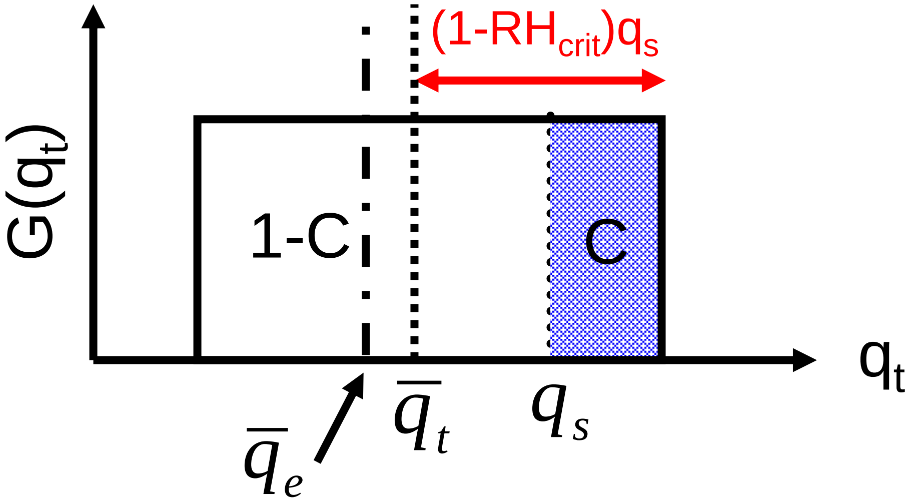


Functional form – needs to fit data but be sufficiently simple

Building a statistical cloud scheme

(3) Diagnostic or prognostic PDF moments

- Some schemes fix the moments (diagnostic e.g. Smith 1990) based on critical RH at which clouds assumed to form.
- Some schemes predict the moments (prognostic, e.g. Tompkins 2002). Need to specify sources and sinks.
- If moments (variance, skewness) are fixed, then statistical schemes are identically equivalent to a RH formulation
- e.g. uniform q_t distribution = Sundqvist formulation



$$\bar{q}_e = q_s(1-(1-RH_{crit})(1-C))$$

$$\bar{q}_v = Cq_s + (1-C)\bar{q}_e$$

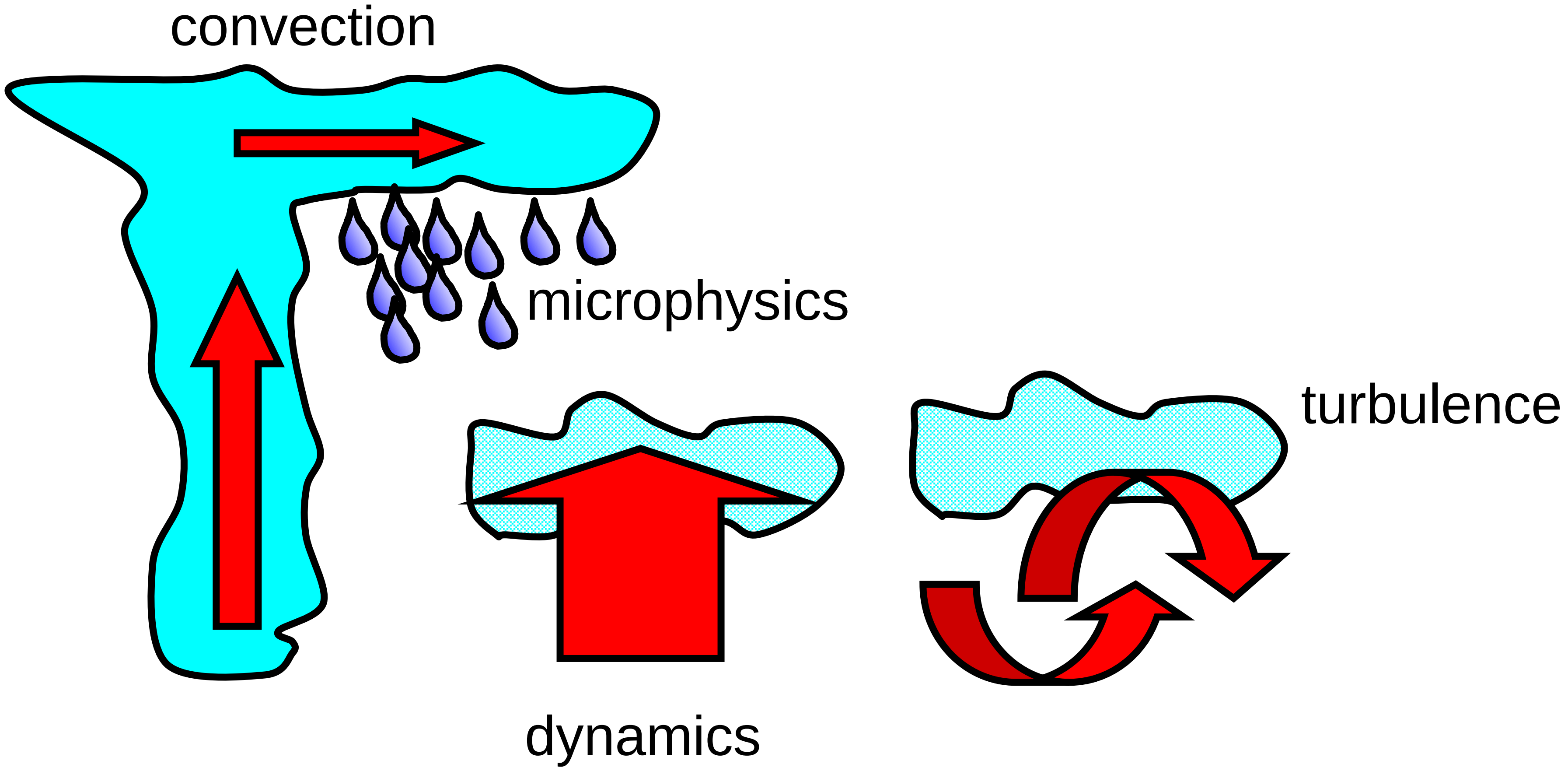
$$RH = \frac{\bar{q}_v}{q_s} = 1-(1-RH_{crit})(1-C)^2$$

Sundqvist formulation!!!

$$\boxed{\therefore C = 1-\sqrt{\frac{1-RH}{1-RH_{crit}}}}$$

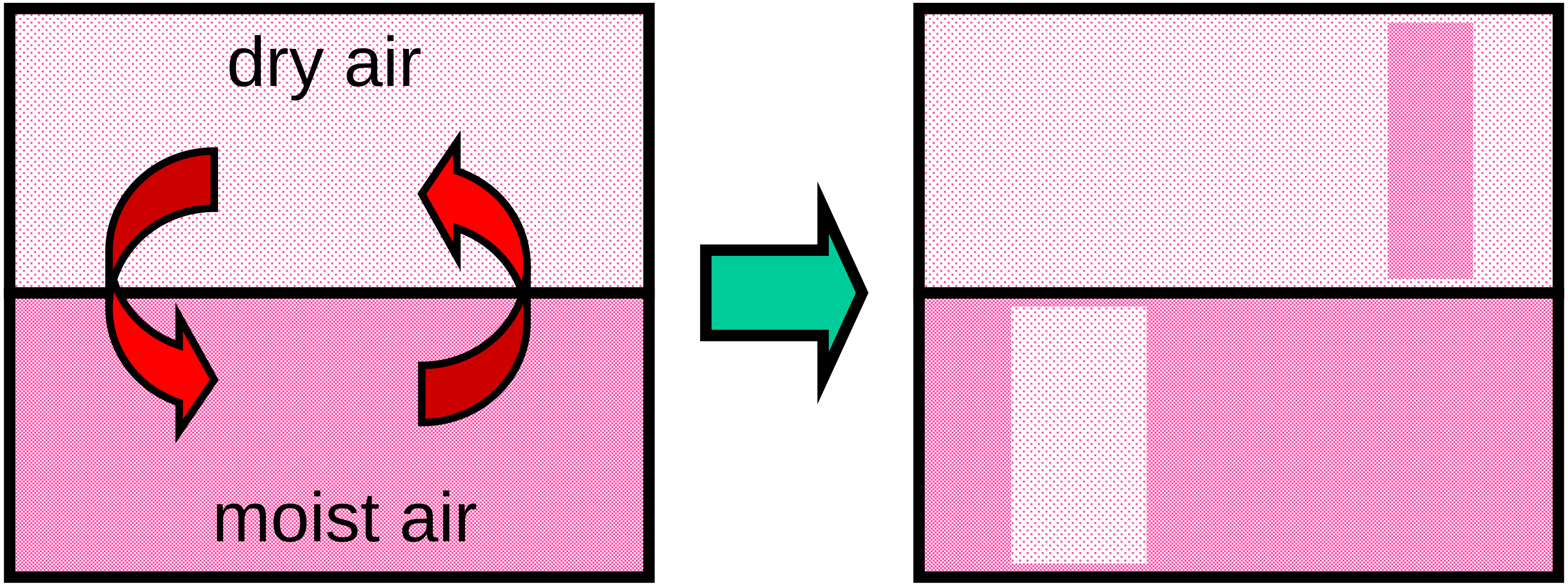
Building a statistical cloud scheme

Processes that can affect PDF moments



Example: Turbulence

In presence of vertical gradient of total water, turbulent mixing can increase horizontal variability

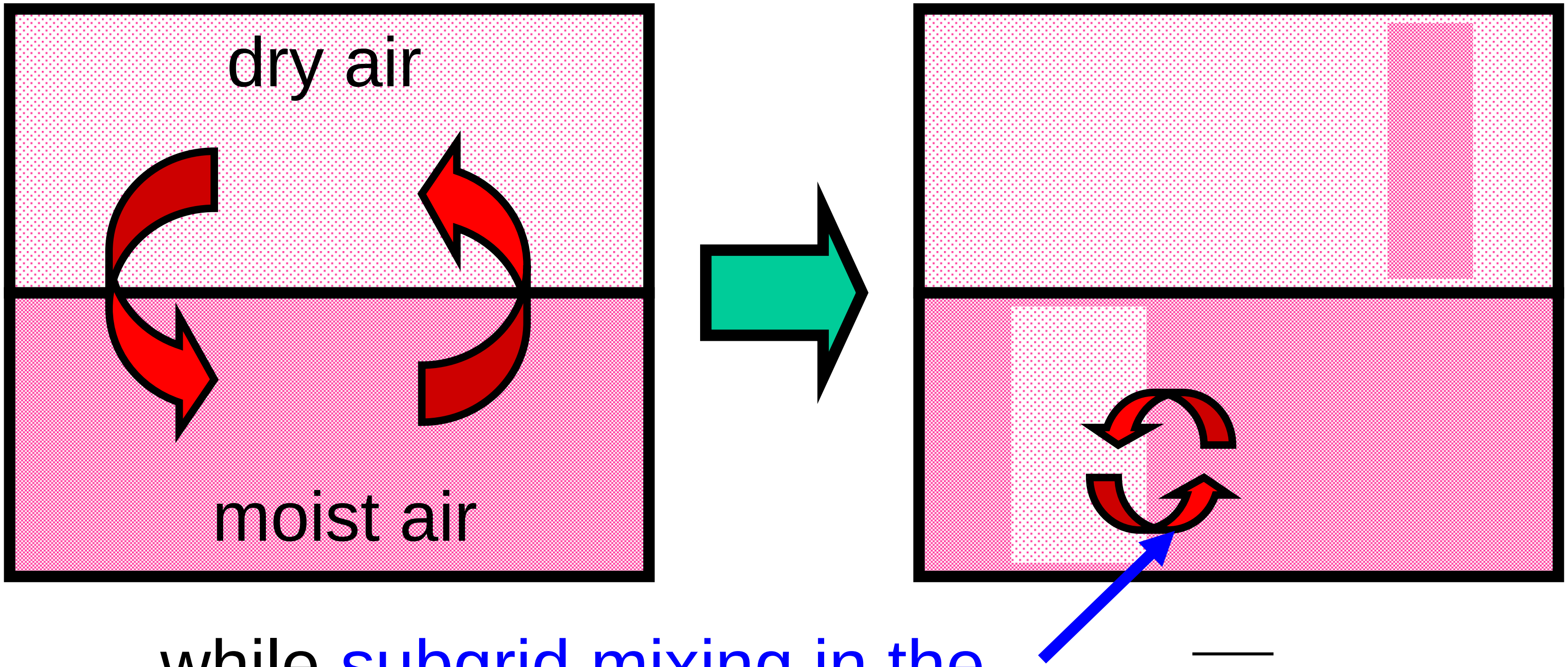


Rate of change of total water variance

$$\frac{d\overline{q_t'^2}}{dt} = -2\overline{w'q_t'}\frac{d\overline{q_t}}{dz}$$

Example: Turbulence

In presence of vertical gradient of total water, turbulent mixing can increase horizontal variability



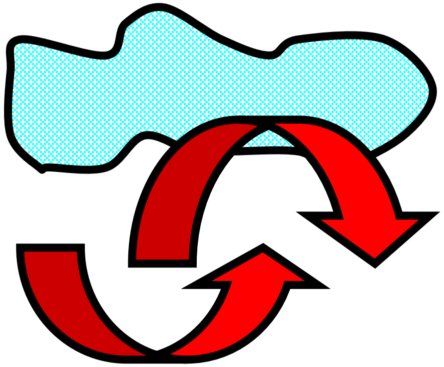
while subgrid mixing in the horizontal plane naturally reduces the horizontal variability

$$\frac{d\overline{q_t'^2}}{dt} = -\frac{q_t'^2}{\tau}$$

Building a statistical cloud scheme

Predicting change of q_t variance due to turbulence

If a process is fast compared to a GCM timestep, an equilibrium can be assumed, e.g. turbulence



$$\frac{d\overline{q_t'^2}}{dt} = -2\overline{w'q_t'}\frac{d\overline{q_t}}{dz} - \frac{\overline{q_t'^2}}{\tau} \xrightarrow{\text{Local equilibrium}} \overline{q_t'^2} = -\tau 2\overline{w'q_t'}\frac{d\overline{q_t}}{dz}$$

Source Dissipation

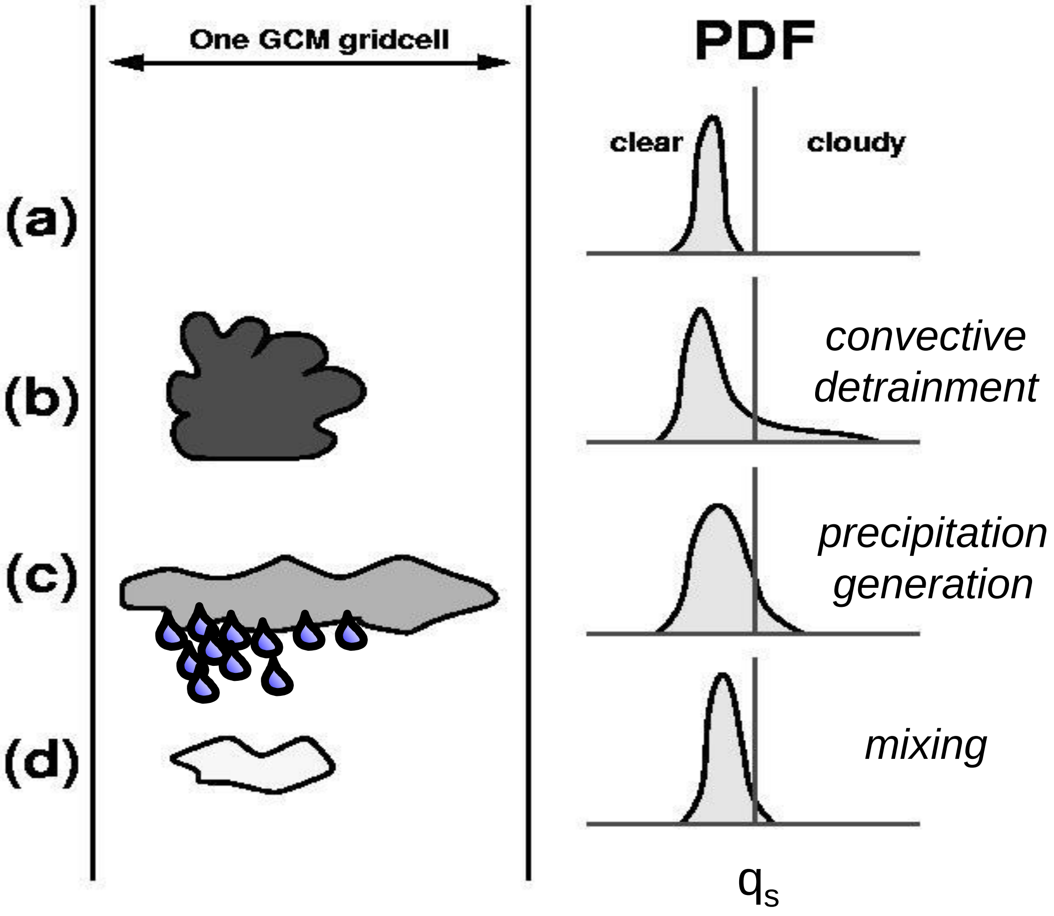
Example: Ricard and Royer, Ann Geophy, (93), Lohmann et al. J. Clim (99)

- Disadvantage:
  - Can give good estimate in boundary layer, but above, other processes will determine variability, that evolve on slower timescales

Building a statistical cloud scheme

Example: Tompkins (2002) prognostic PDF

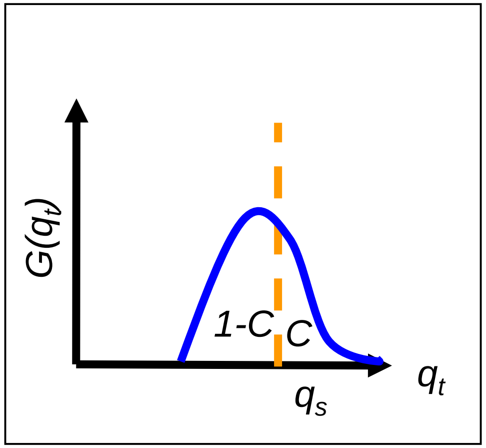
- Tompkins (2002) prognostic statistical scheme (implemented in ECHAM5 climate GCM).
- Prognostic equations are introduced for variables representing the mean, variance and skewness of the total water PDF (Beta fn)
- Some of the sources and sinks are rather ad-hoc in their derivation!



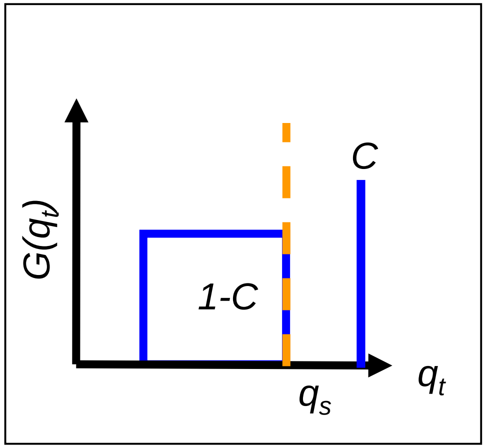
The ECMWF Cloud Scheme

Comparison with Tompkins prognostic PDF scheme

Tompkins (2002)



Tiedtke(1993) in ECMWF IFS



A bounded beta function with positive skewness.

Effectively 3 prognostic variables:

Mean q_t
Variance of PDF
Skewness of PDF

A mixed 'uniform-delta' total water distribution is assumed for the condensation process.

3 prognostic variables:

Humidity, q_v
Cloud condensate, q_c
Cloud fraction, C

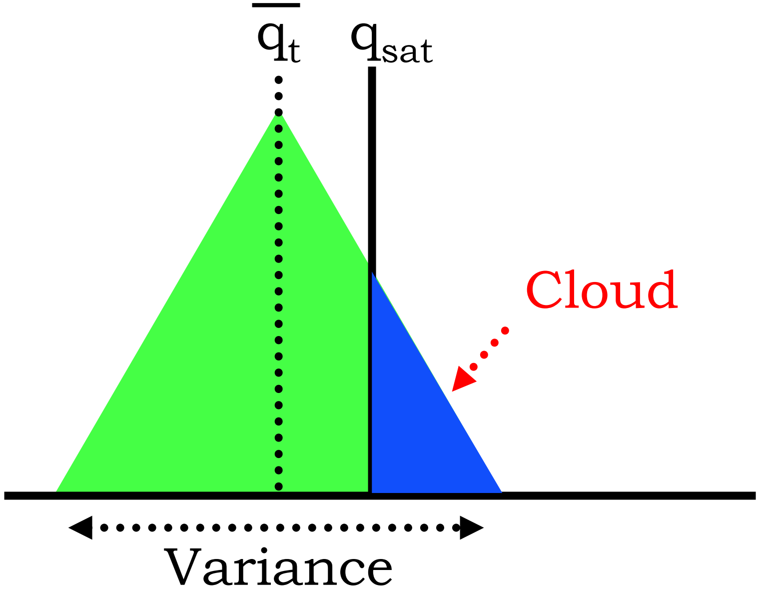
Same degrees of freedom ?

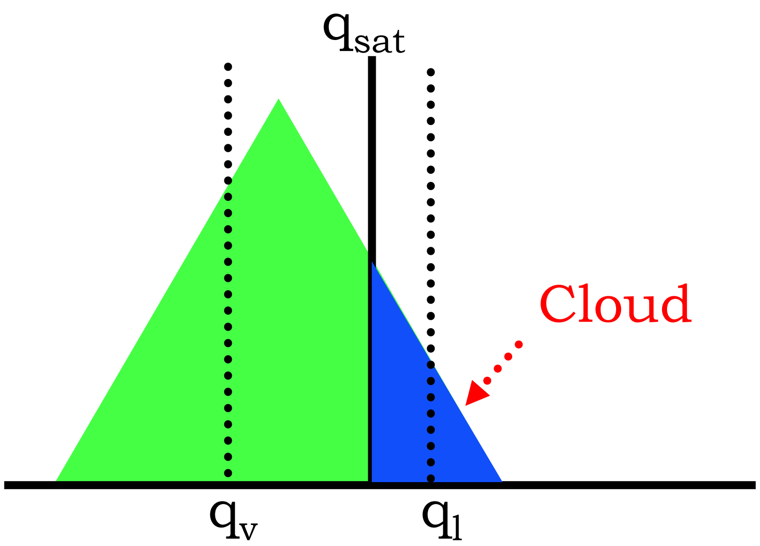
Prognostic statistical PDF scheme:
Which prognostic variables/equations?

Take a 2 parameter distribution & partially cloudy conditions

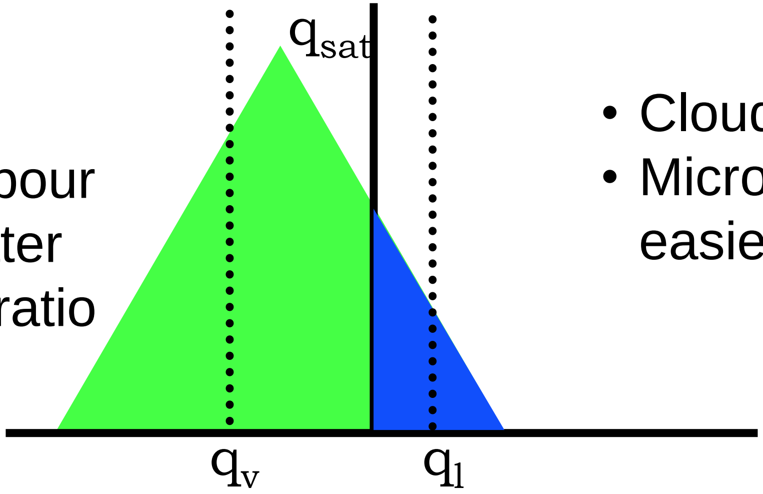
(1) Can specify distribution with
- (a) Mean
- (b) Variance of total water

(2) Can specify distribution with
- (a) Water vapour
- (b) Cloud water mass mixing ratio





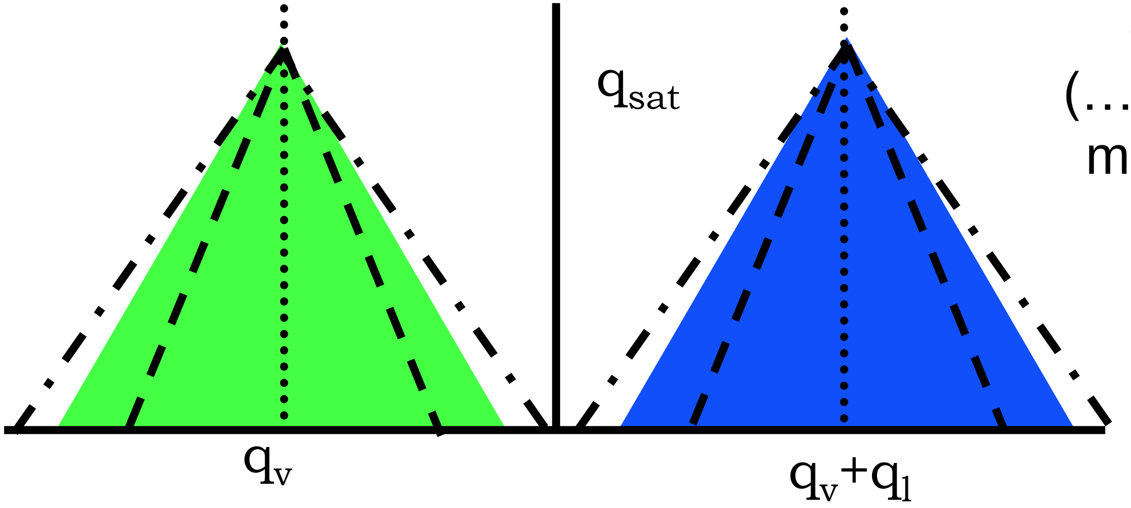
Prognostic statistical scheme:
(1) Water vapour and cloud water ?



(a) Water vapour
(b) Cloud water
mass mixing ratio

- Cloud water budget conserved.
- Microphysical sources and sinks easier to parametrize.

But problems arise in...



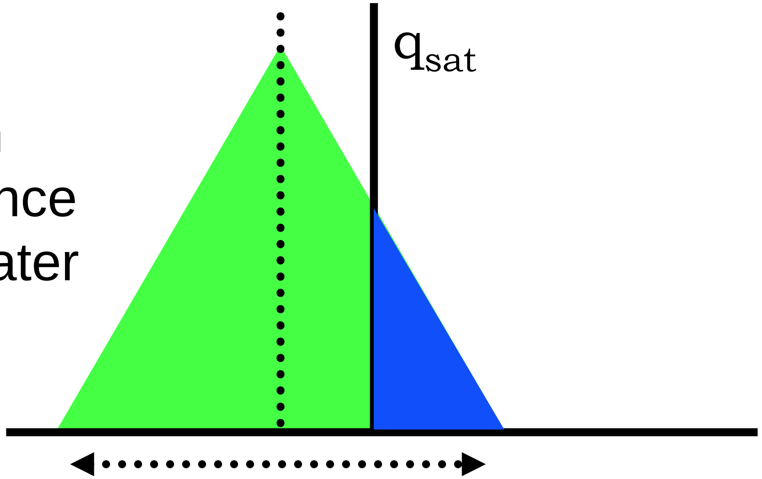
Clear sky
conditions
(turbulence)

Overcast
conditions
(…convection +
microphysics)

Need to specify
width, RH_{crit}

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

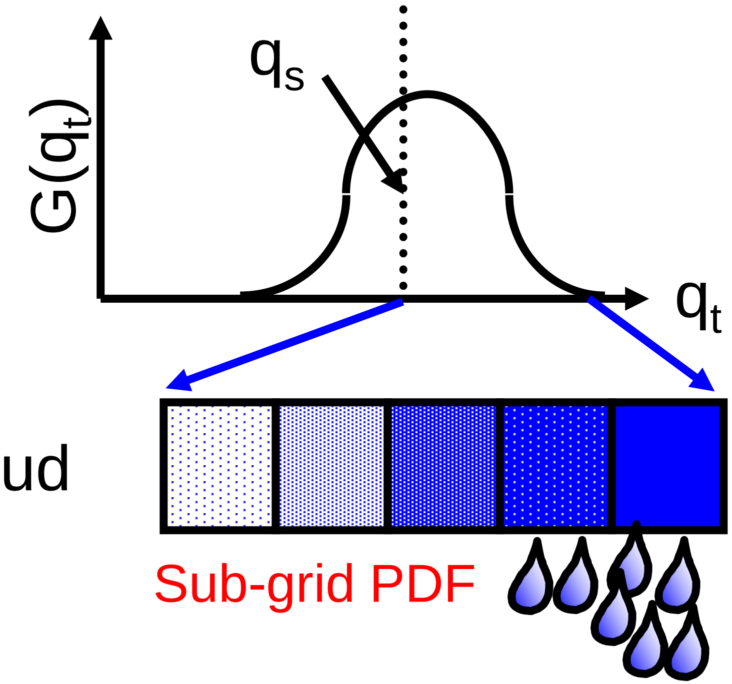
(a) Mean
(b) Variance
of total water

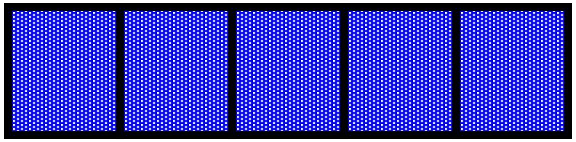


- “Cleaner solution”.
- But conservation of liquid water may be difficult (eg. advection)
- Parametrizing microphysics sources, sinks can be more difficult.

Cloud inhomogeneity in microphysics

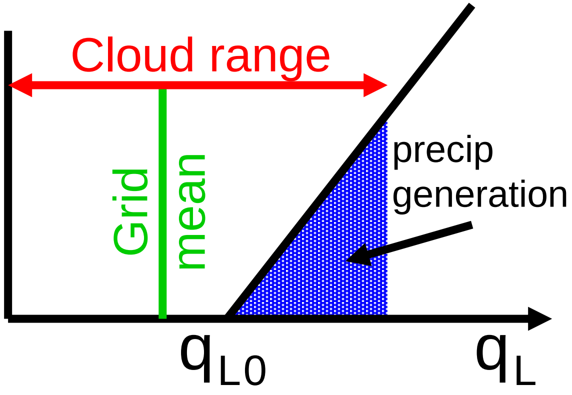
Many current microphysical schemes use the grid-mean or cloud fraction cloud mass (i.e: neglect in-cloud variability)





Homogeneous

cloud



For example, Kessler autoconversion scheme: Result is not equal in the two cases since microphysical processes are non-linear

In the homogeneous case the grid mean cloud is less than threshold and gives zero precipitation formation

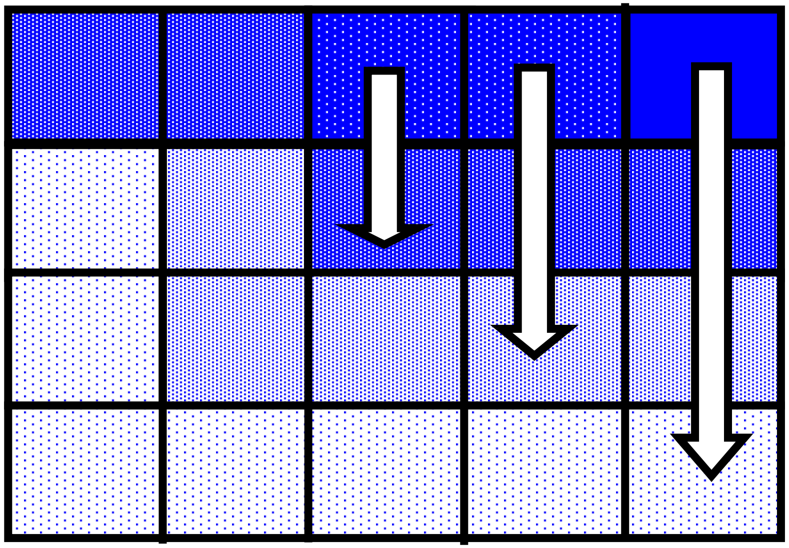
Prognostic statistical PDF scheme:
Knowing the PDF….

- **Advantages**
  - Information concerning subgrid fluctuations of humidity and cloud condensate is available (for all parametrizations)
  - Use of underlying PDF means cloud variables (condensate, cloud fraction) are always self-consistent.
- **Challenges…**
  - Deriving these sources and sinks rigorously is difficult, especially for higher order moments for more complex PDFs!
  - Limited observations to define PDF
  - If variance and skewness are used instead of cloud water and humidity, conservation of the latter is not ensured.
  - Is a fixed PDF shape, even with variable moments, able to represent the wide range of variability in the atmosphere?
  - How do we treat the ice phase, supersaturation, mixed-phase cloud, sedimentation? These are important questions!

Subgrid heterogeneity:

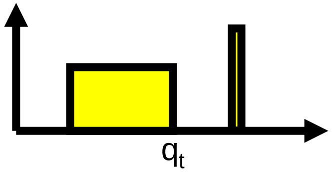
How do we treat subgrid heterogeneity and sedimentation ?

- Analytically, can quickly get intractable
- Subcolumn approach, as for radiation? but computationally expensive.
- Memory of subgrid precipitation fluxes?



Sub-grid cloud parametrization

Current status in GCMs…?

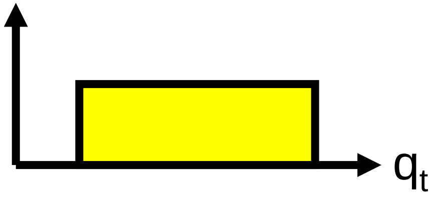


Uniform-delta:

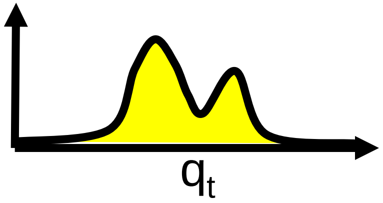
Tiedtke (1993)

- The ECMWF global NWP model has prognostic water vapour, cloud water and cloud fraction. With a uniform function for heterogeneity in the clear air and a delta function (homogeneous) in-cloud.

- The UK Met Office global NWP model (PC2 scheme) also has prognostic water vapour, cloud water and cloud fraction.



- Many other operational global NWP/climate models have diagnostic sub-grid cloud schemes, e.g. NCEP GFS: Sundquist et al. (1989)



Double-Gaussian

(CLUBB)

- Research is ongoing for statistical schemes with prognostic PDF moments (e.g. Tompkins scheme tested in ECHAM, CLUBB tested in CAM).

Summary

Representing subgrid scale heterogeneity

- Representing sub-gridscale heterogeneity in GCMs is important for cloud formation, microphysical processes, radiation etc.
- Many different approaches have been tried, with varying degrees of complexity to represent the variability observed in the atmosphere.
- More degrees of freedom allow greater flexibility to represent the real atmosphere, but we need to have enough knowledge/information to understand and constrain the problem (form of pdf/sources/sinks)!
- Cloud, convection and BL turbulence are all part of the subgrid heterogeneity – active research into unified schemes.
- Statistical prognostic PDF schemes have many advantages but challenges remain for clouds other than warm-phase boundary layer cloud!
- However, we should continue to strive for a **consistent representation of this heterogeneity** for all processes in the model.

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