Numerical Weather Prediction
Parametrization of Subgrid Physical Processes

Clouds (2)

Sub-grid Cloud Cover

(or "Sub-grid heterogeneity of cloud and humidity")

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(With thanks to Adrian Tompkins and Christian Jakob)

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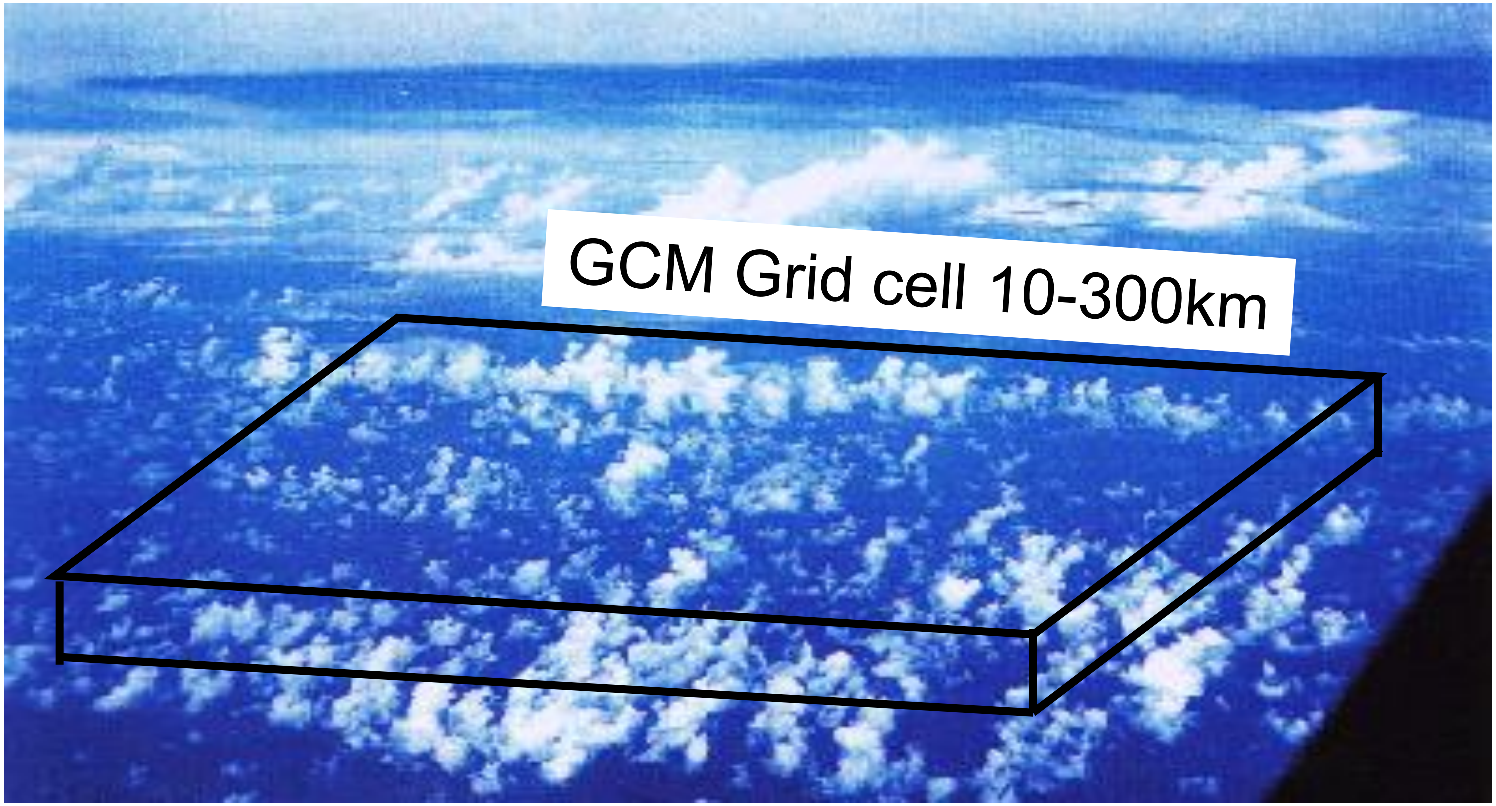
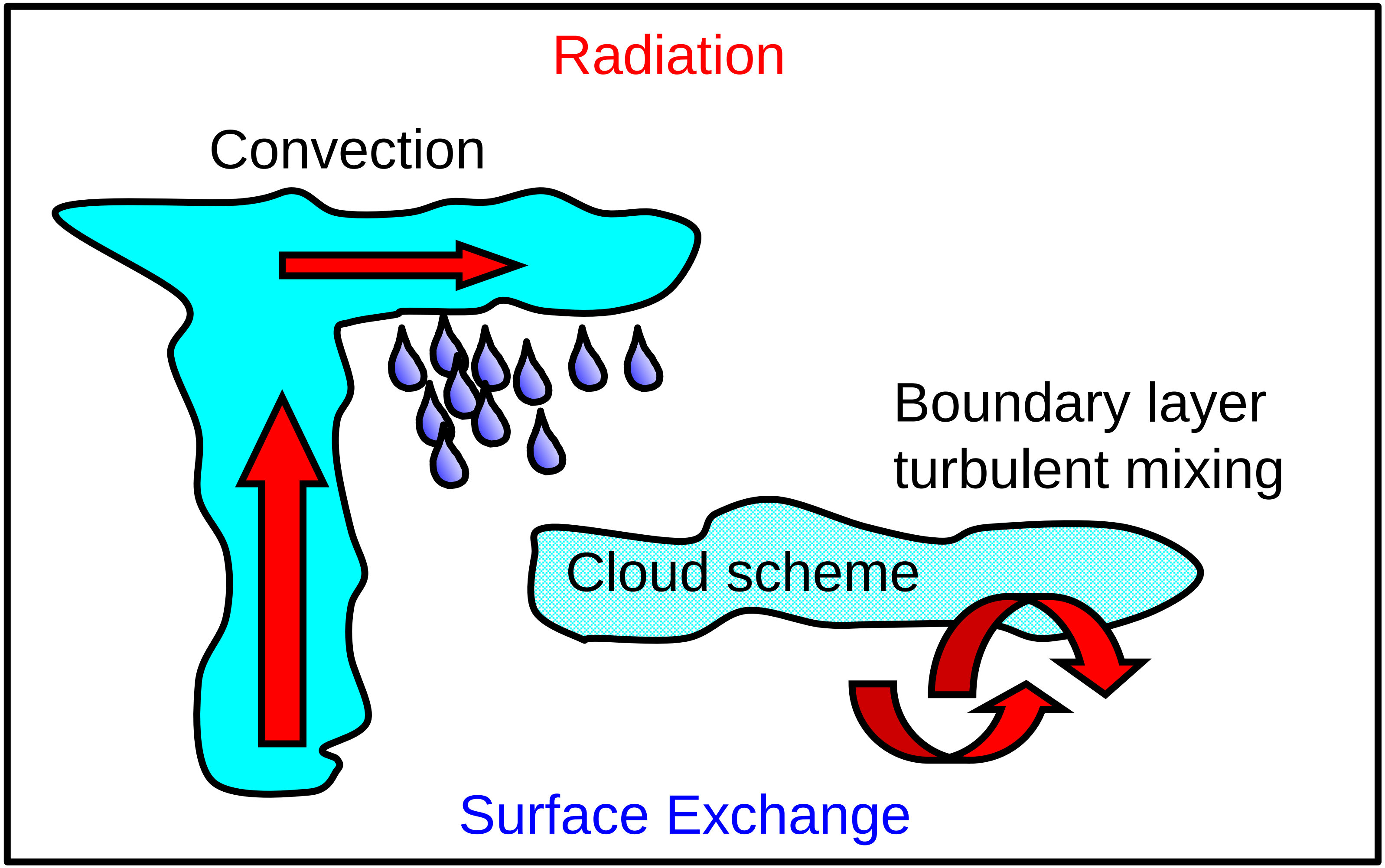
Clouds in GCMs:
Representing sub-grid heterogeneity

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…



Why represent heterogeneity?

Important scales of cloud cover & reflectance

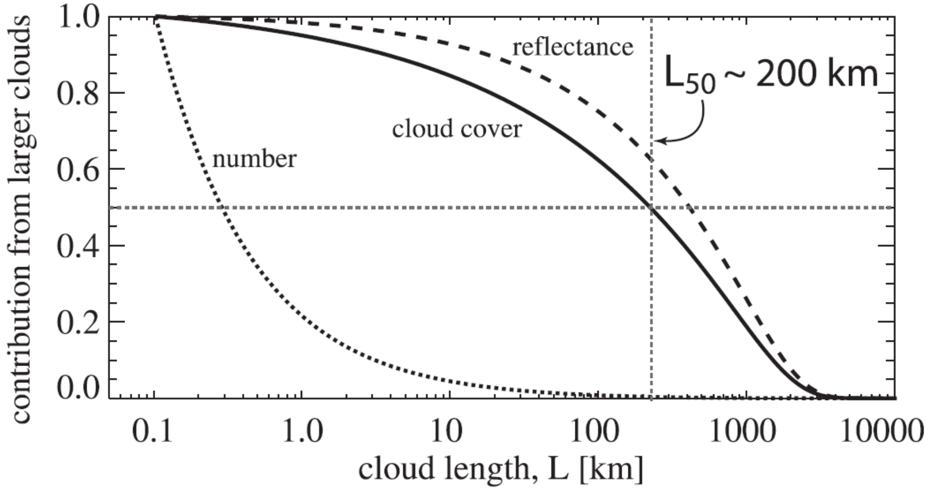


Fig 6. Contribution to global cloud cover (solid), number (dotted) and visible reflectance (dashed) from clouds with chord lengths greater than L (based on MODIS, aircraft and NWP data).

(from Wood and Field 2011, JClim)

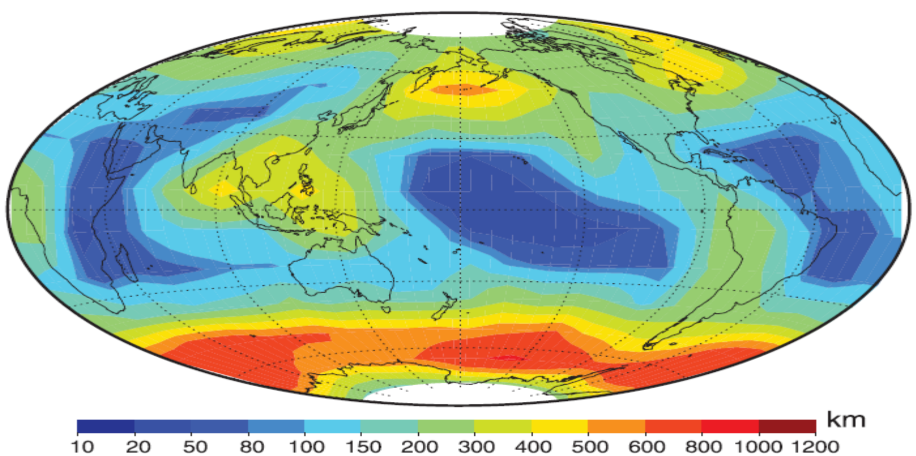


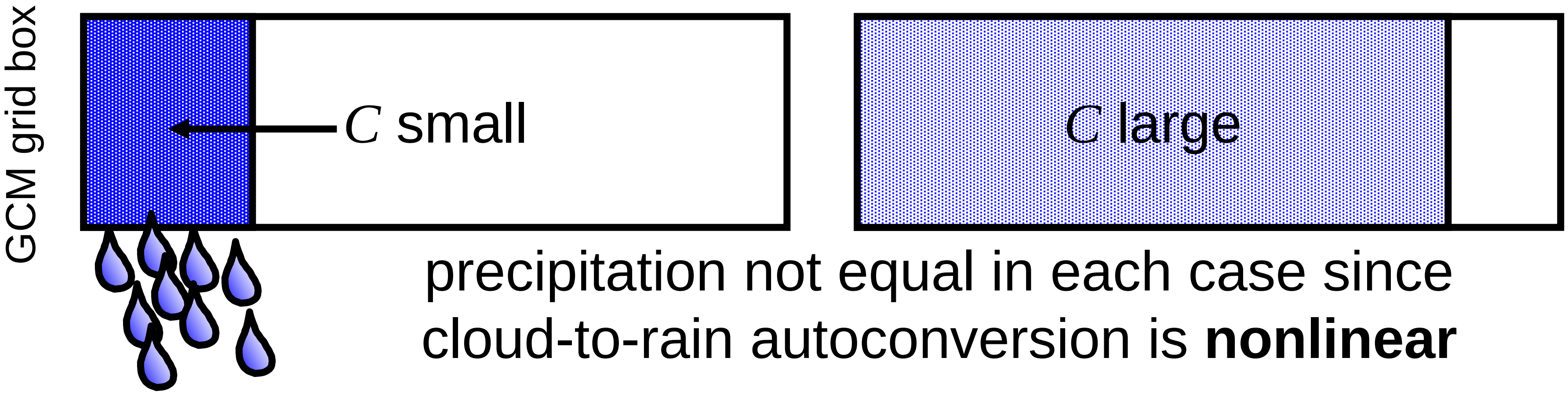
Fig 8. Map of the cloud size for which 50% of cloud cover comes from larger clouds (from 2 years of MODIS data)

15% of global cloud cover comes from clouds smaller than 10 km (smaller scales dominate over subtropical ocean)

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

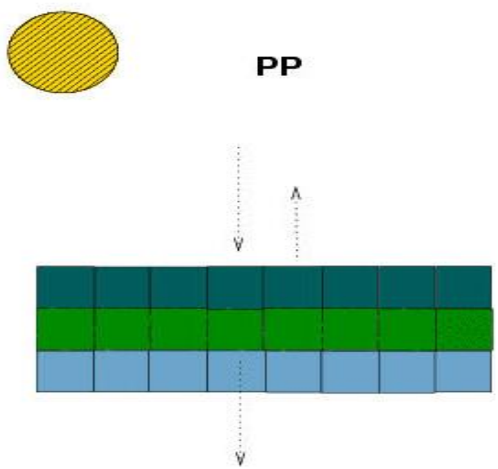


precipitation not equal in each case since cloud-to-rain autoconversion is **nonlinear**

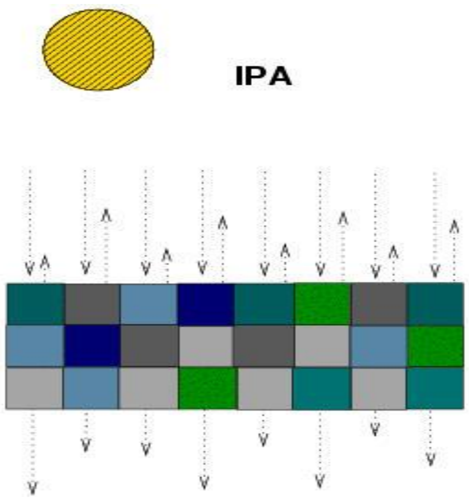
- Complex microphysics perhaps a wasted effort if assessment of cloud fraction C is poor!
- In addition, in-cloud condensate heterogeneity should also be represented, i.e. not all the cloud is precipitating?

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)

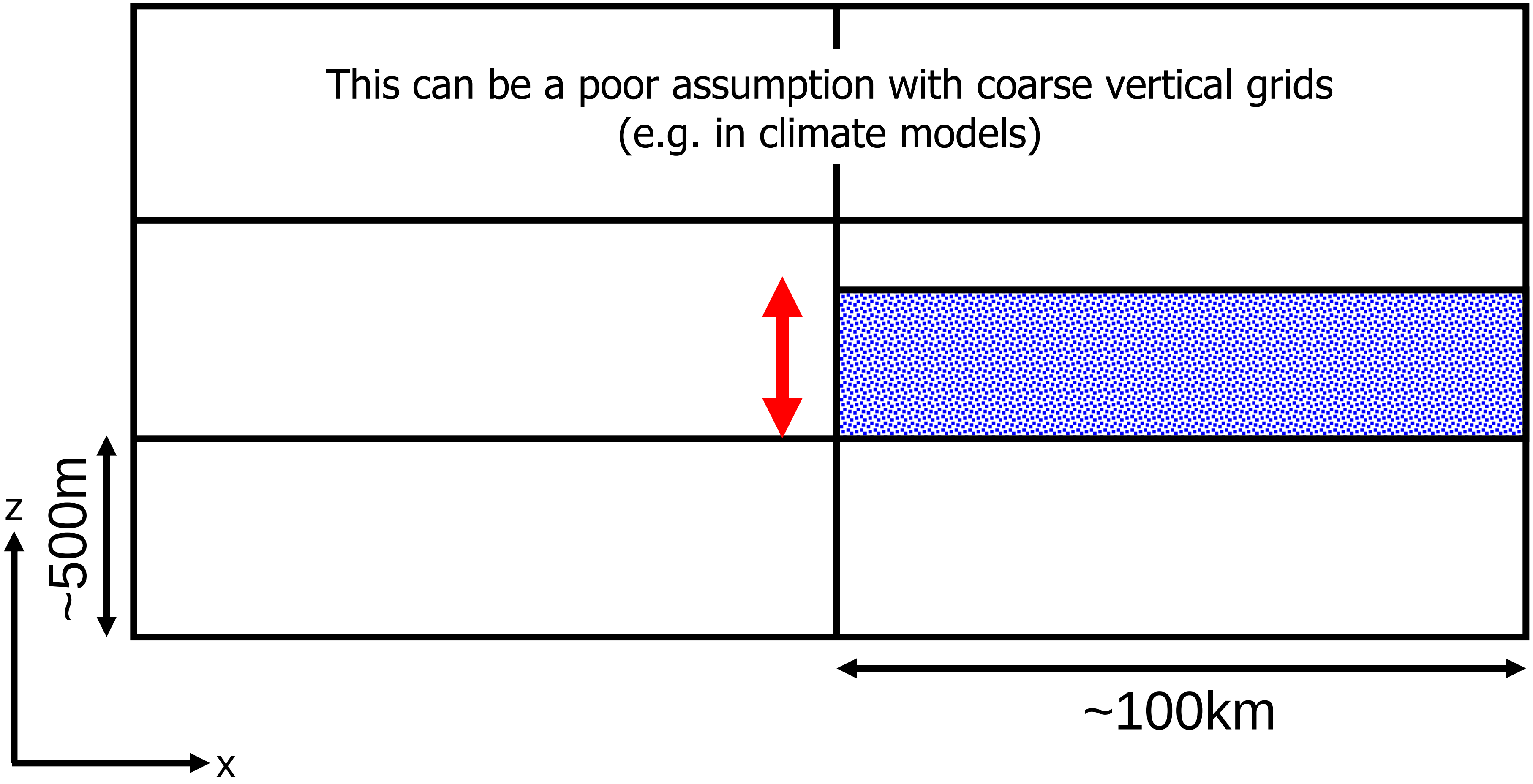


Independent Column Approximation, e.g. MCICA

Macroscale Issues of Parameterization

VERTICAL COVERAGE

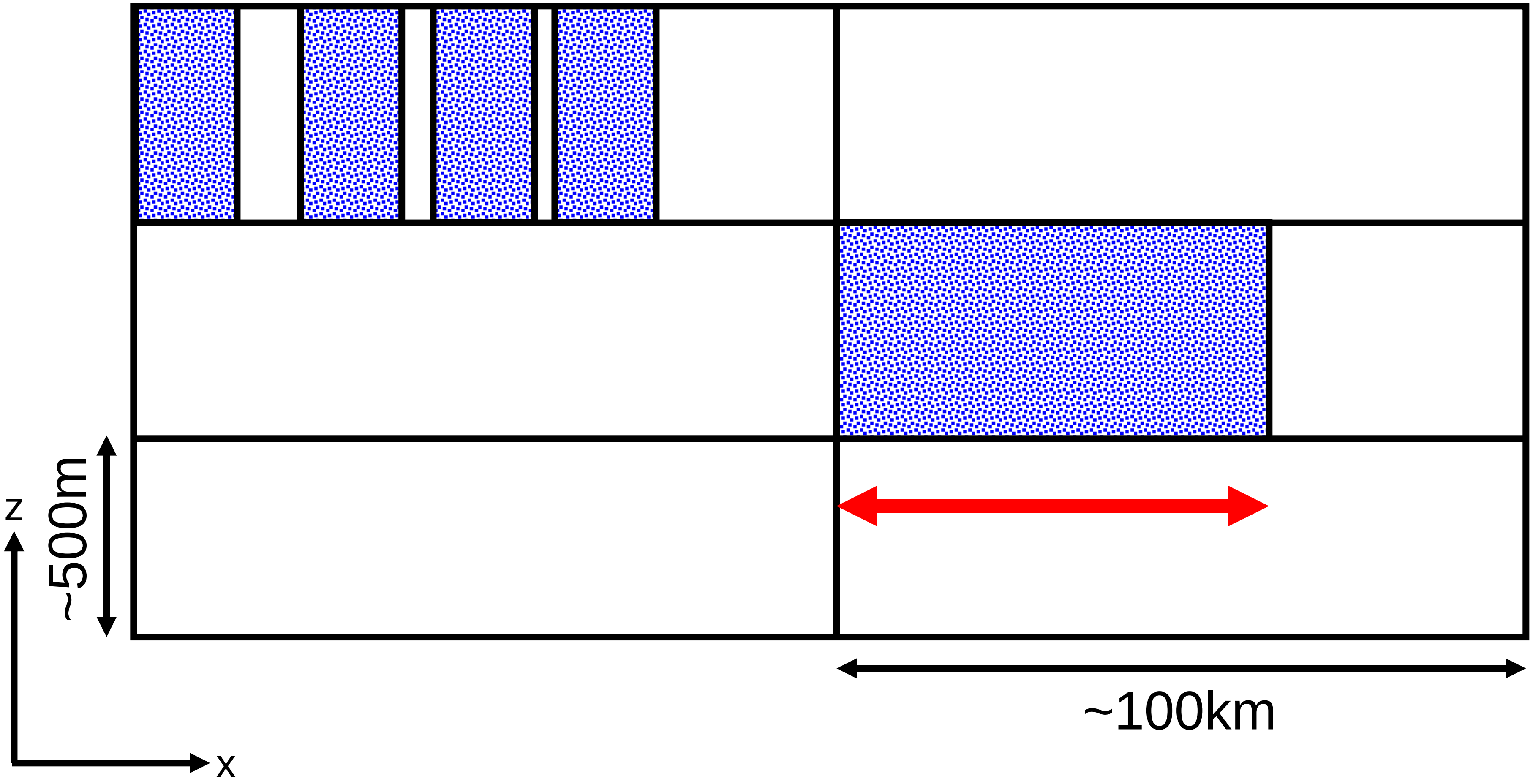
Most models assume that this is 1



Macroscale Issues of Parameterization

HORIZONTAL COVERAGE, *C*

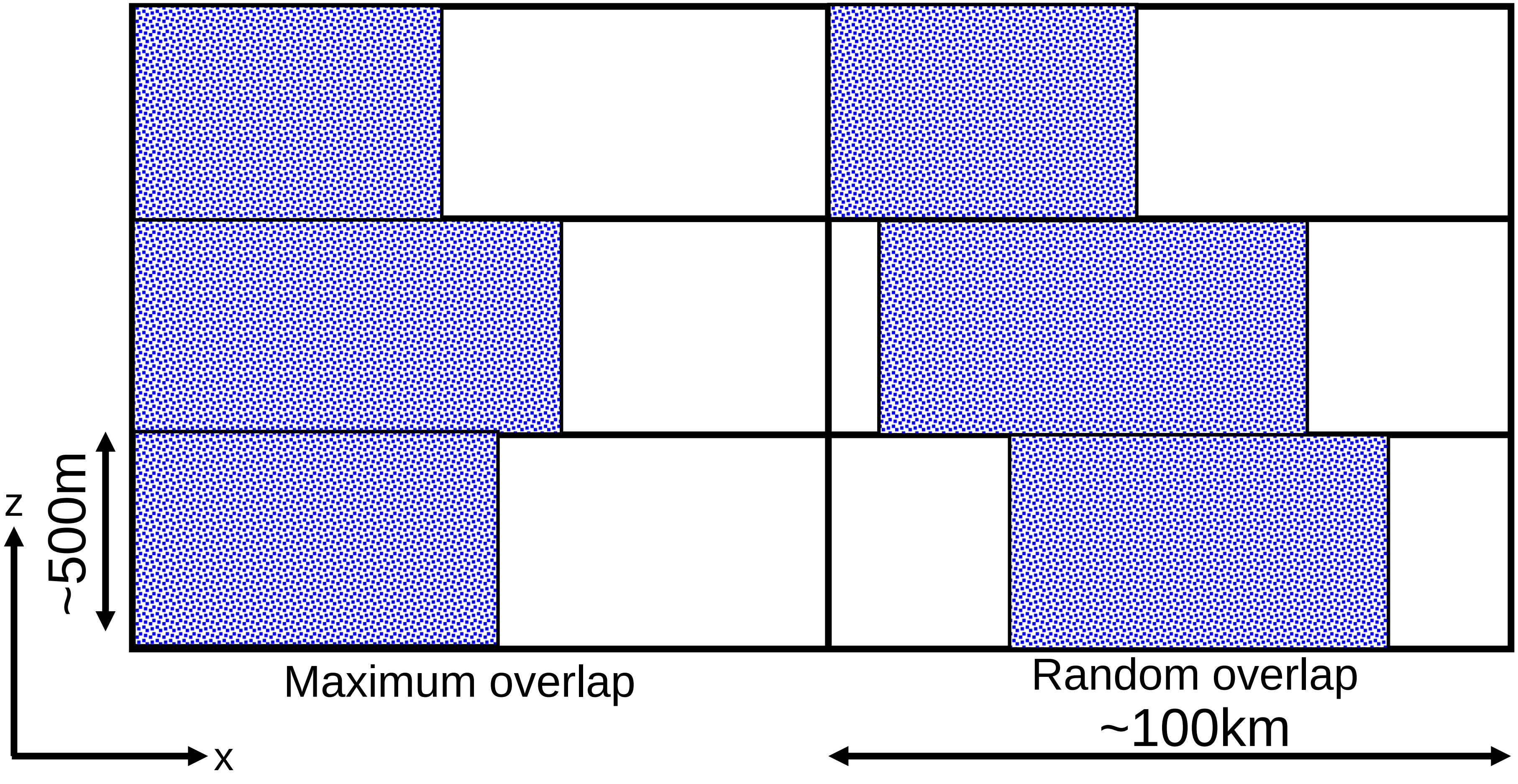
Spatial arrangement ?



Macroscale Issues of Parameterization

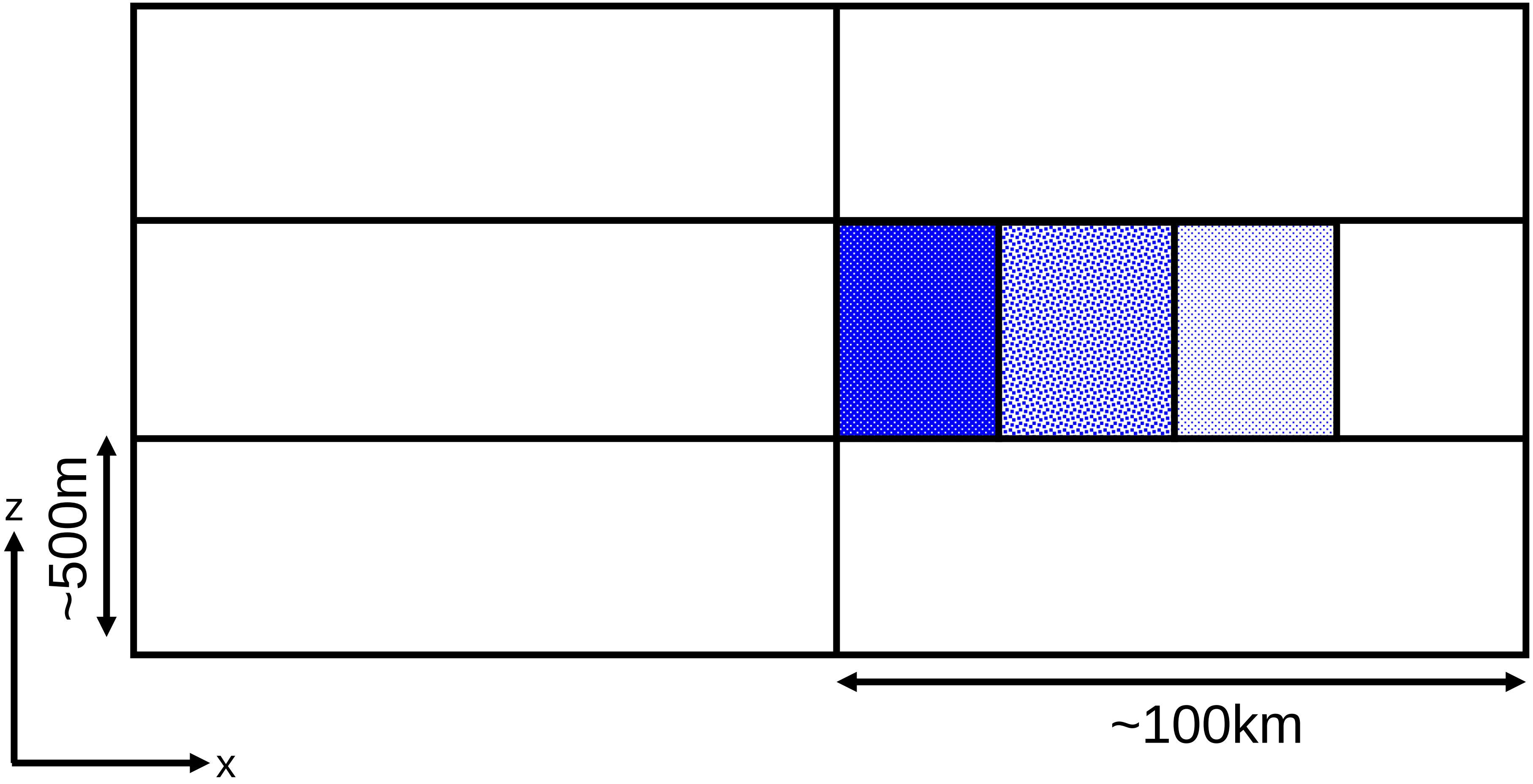
Vertical overlap of cloud

Important for radiation and microphysics interaction



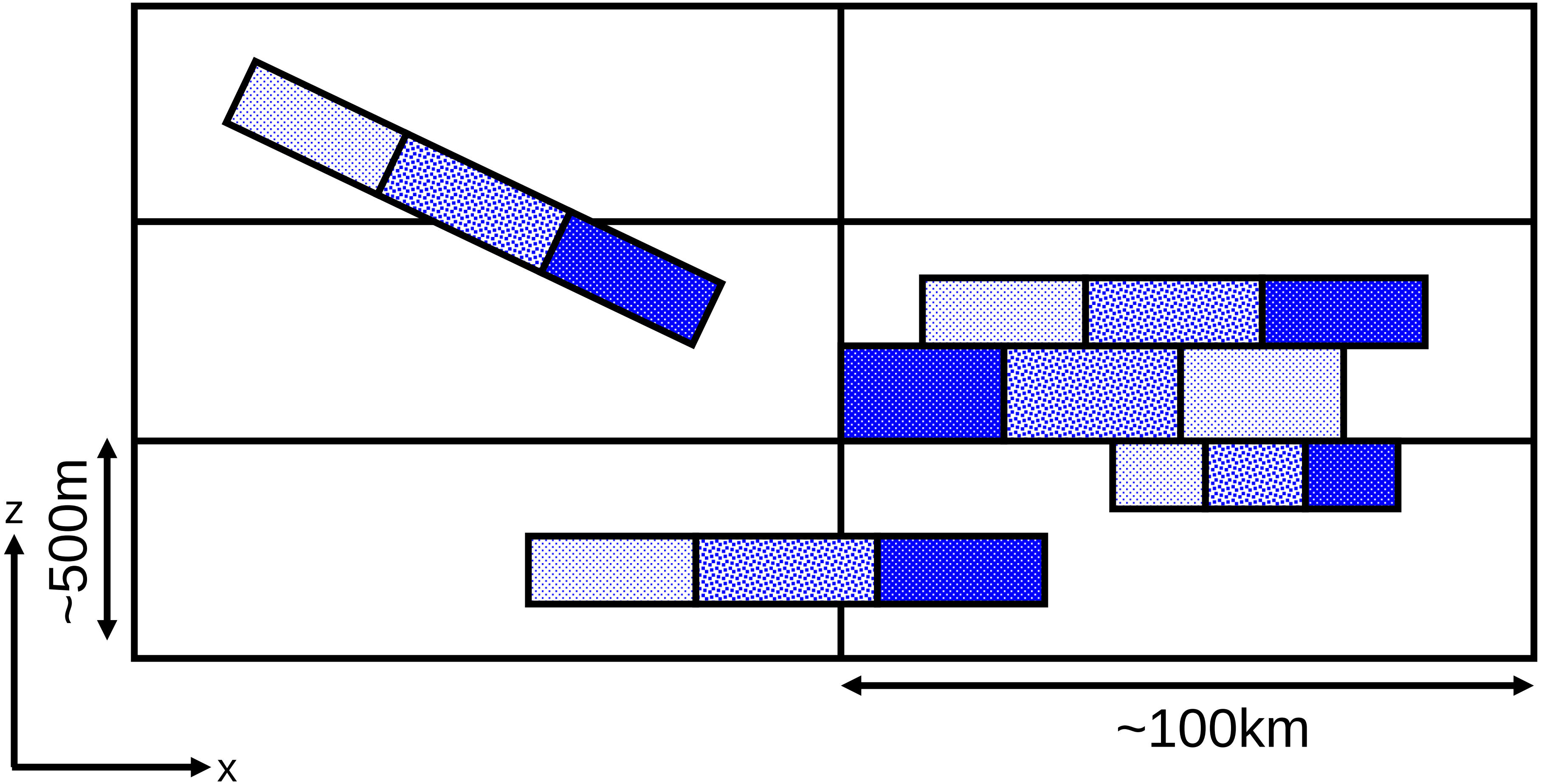
Macroscale Issues of Parameterization

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)

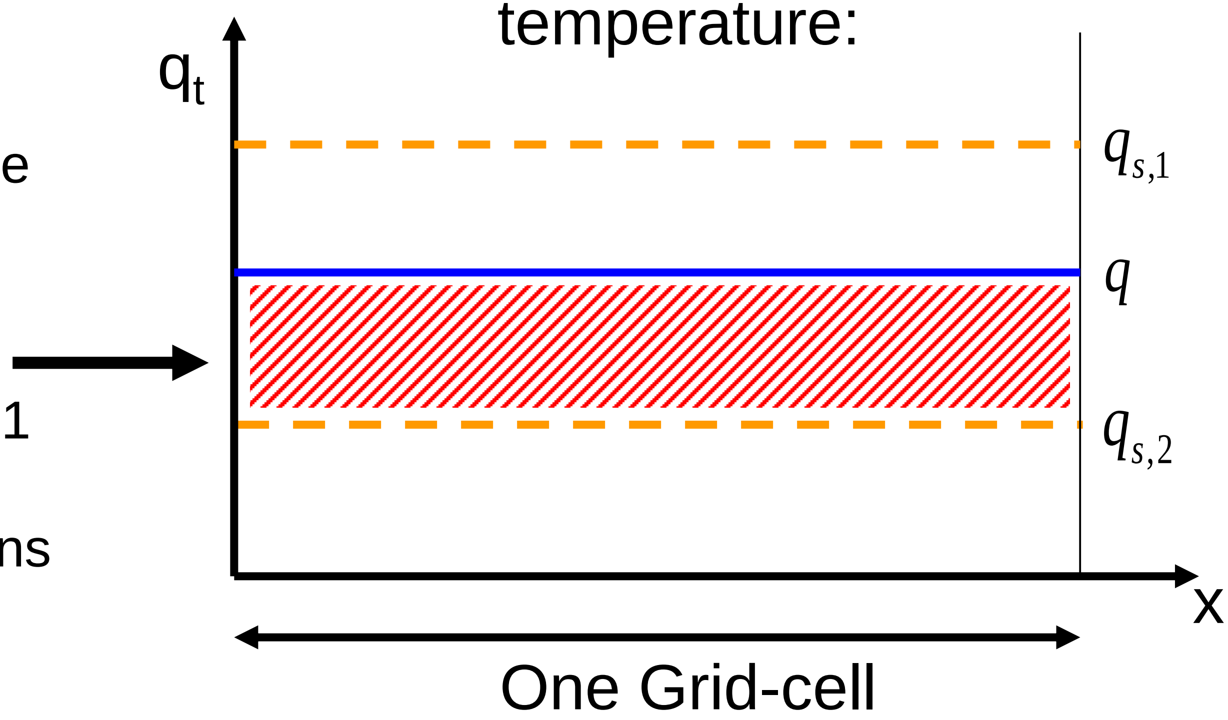
$$q_v = q_s \qquad q_c = q_t - q_s$$

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

Partial cloud cover

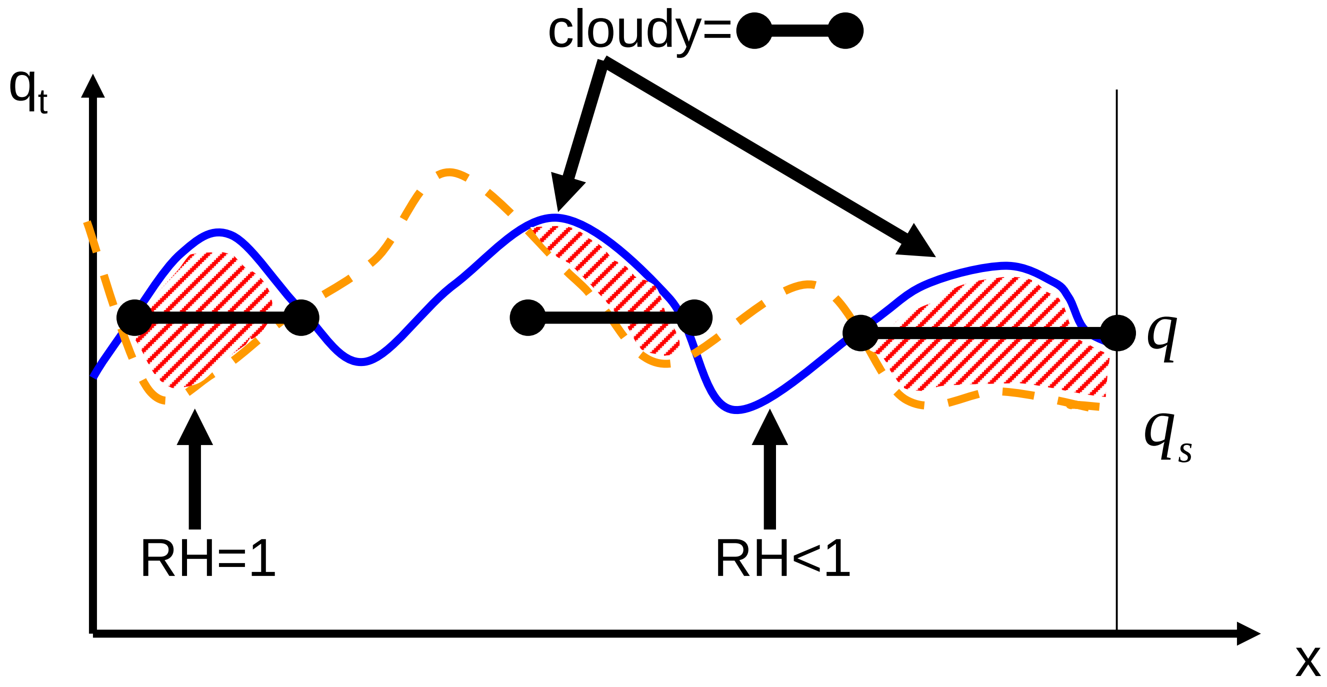
Homogeneous distribution of water vapour and temperature:

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



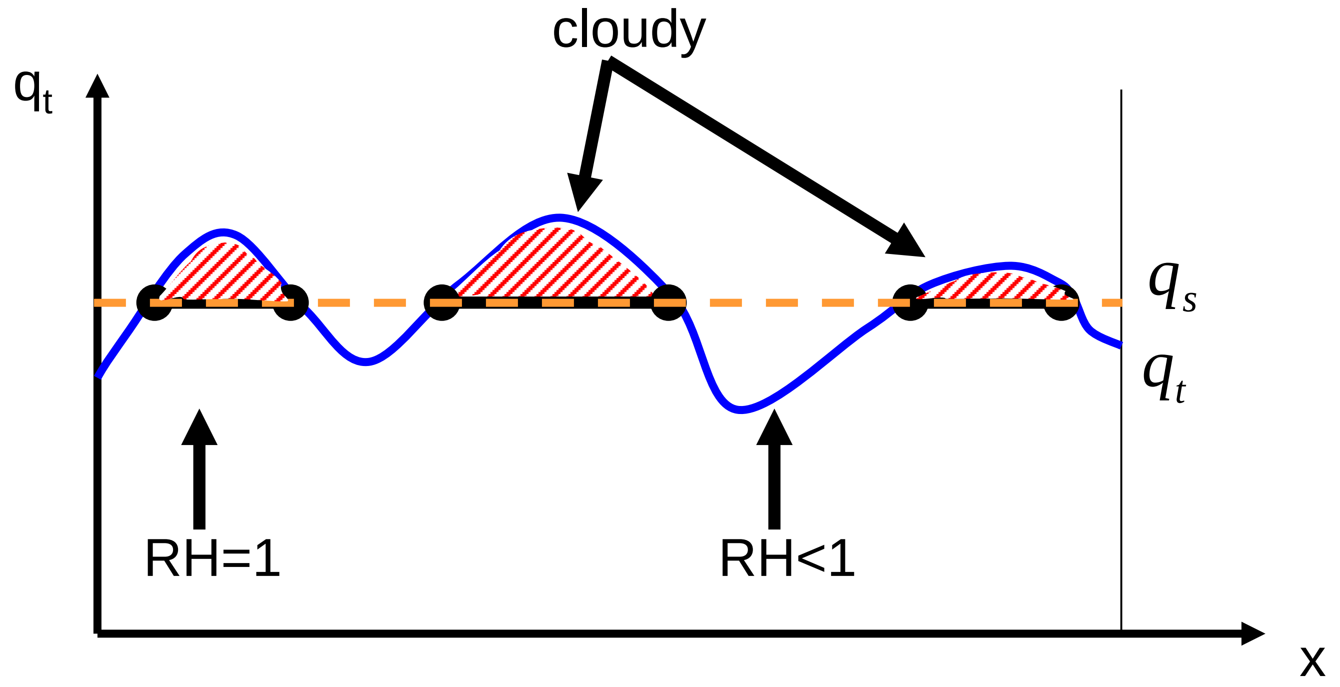
Partial coverage of a grid-box with clouds is only possible if there is an inhomogeneous distribution of temperature and/or humidity.

Heterogeneous Distribution of *T* and *q*



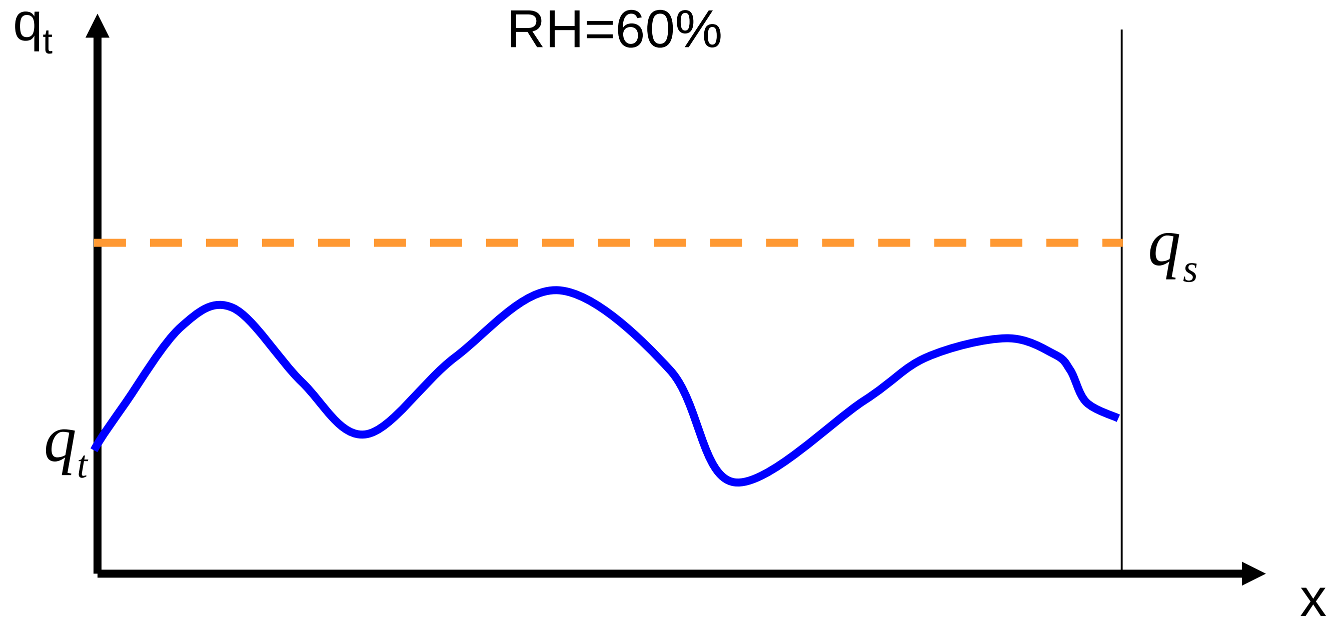
Another implication of the above is that clouds must exist before the grid-mean relative humidity reaches 1.

Heterogeneous Distribution of *q* only

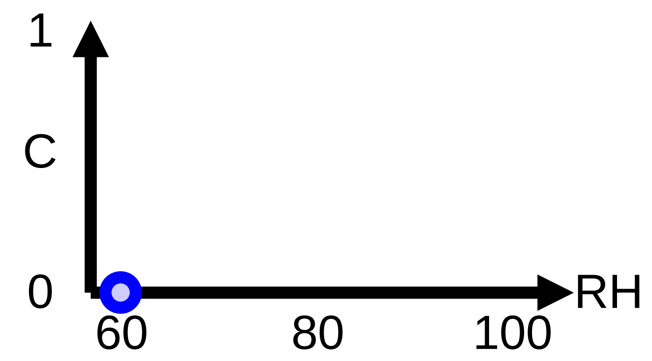


- The interpretation does not change much if we only consider humidity variability
- Throughout this talk I will neglect temperature variability
- Analysis of observations and model data indicates humidity fluctuations are more important *most* of the time.

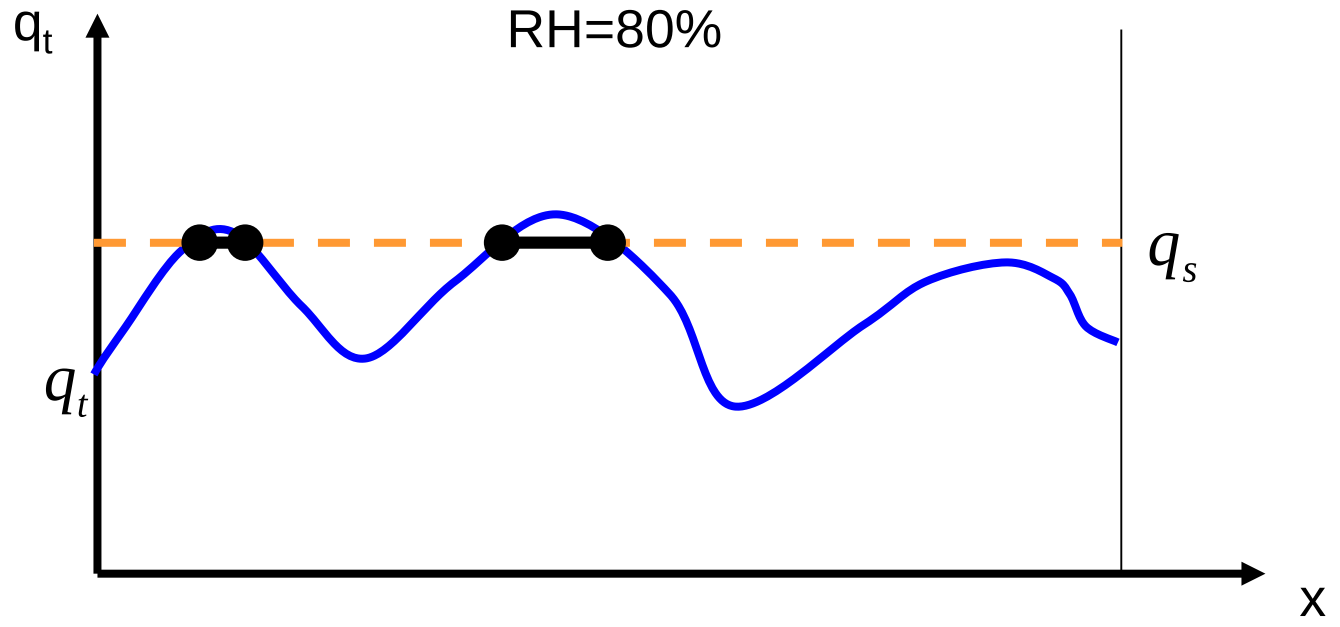
Simple Diagnostic Cloud Schemes:
Relative Humidity Schemes



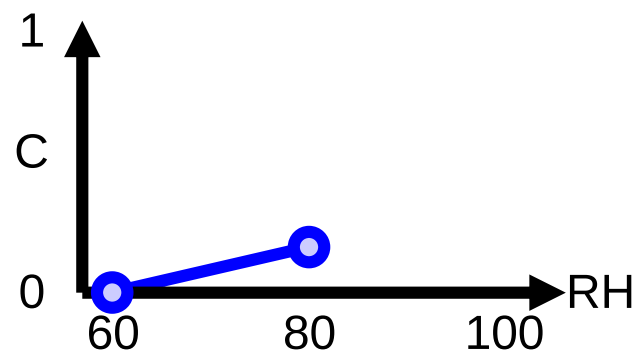
Take a grid cell with a certain (fixed) distribution of total water.
At low mean RH, the cloud cover is zero, since even the moistest part of the grid cell is subsaturated



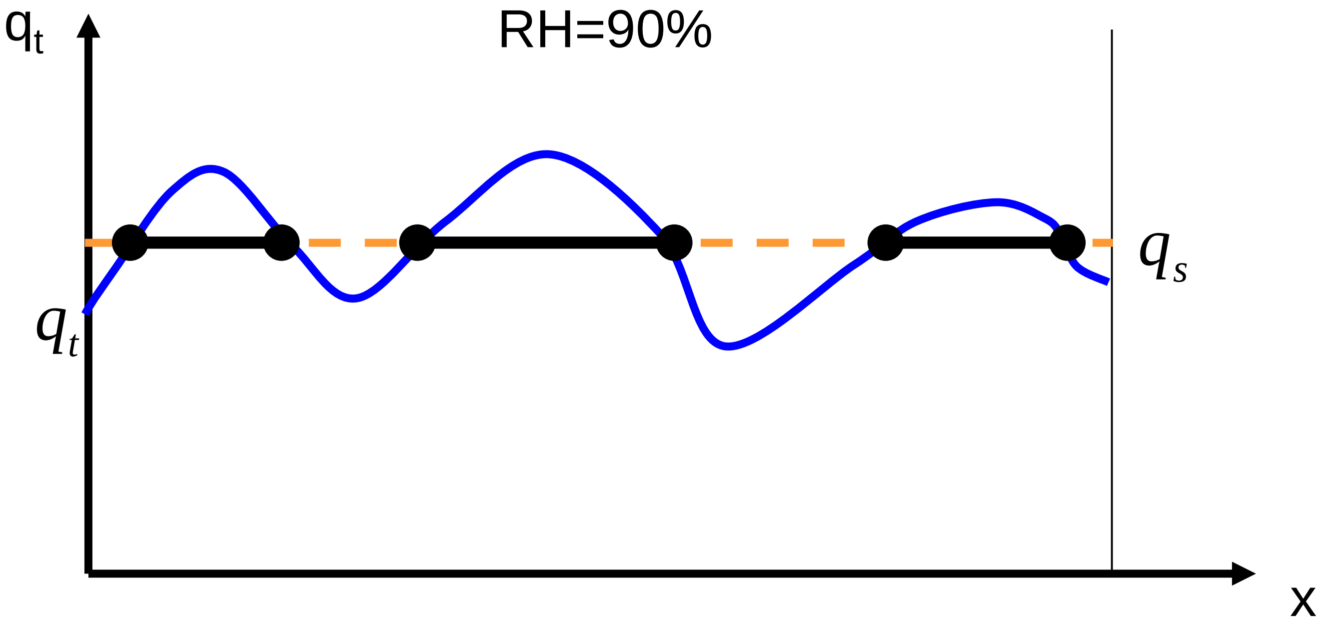
Simple Diagnostic Cloud Schemes:
Relative Humidity Schemes



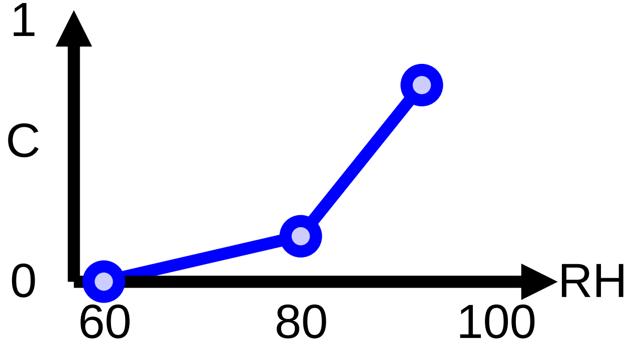
Add water vapour to the gridcell, the moistest part of the cell become saturated and cloud forms. The cloud cover is low.



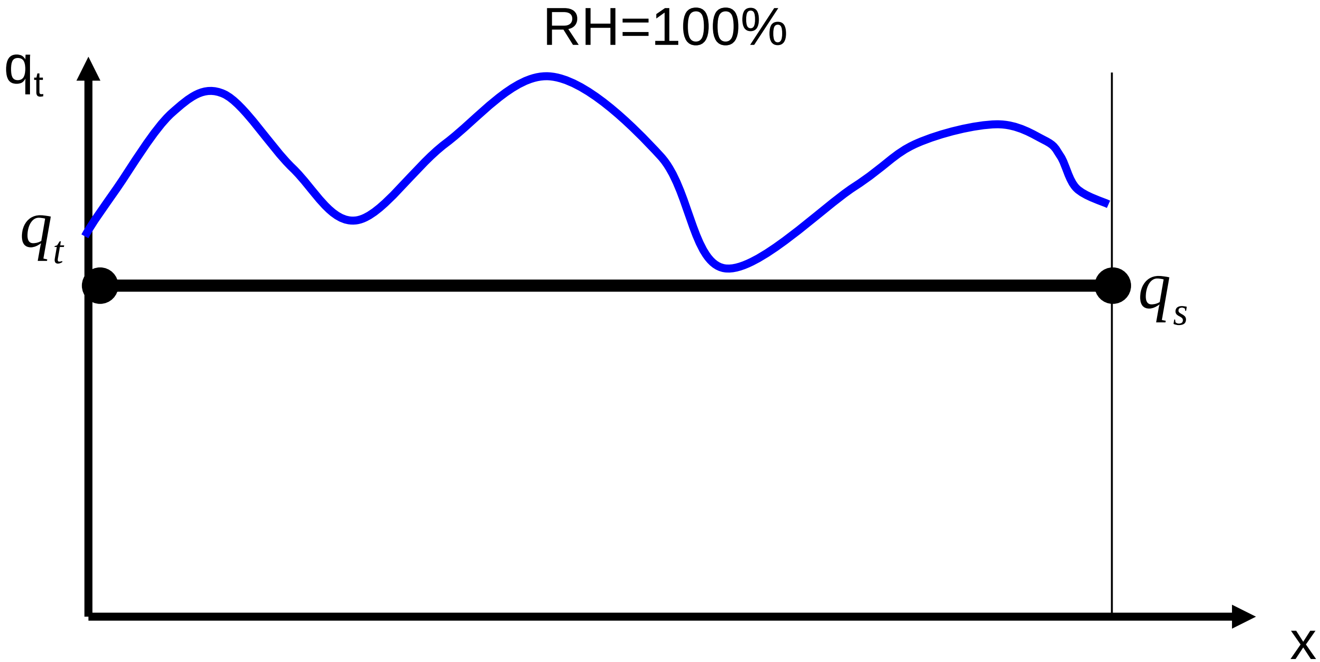
Simple Diagnostic Cloud Schemes:
Relative Humidity Schemes



Further increases in RH increase the cloud cover

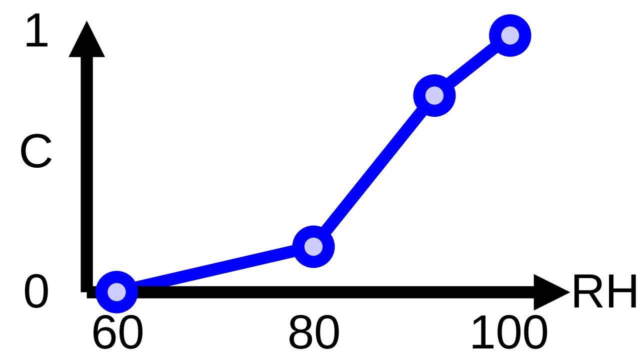


Simple Diagnostic Cloud Schemes:
Relative Humidity Schemes



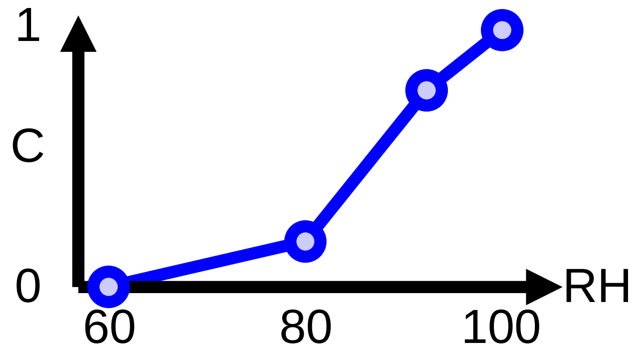
- The grid cell becomes overcast when RH=100%,due to lack of supersaturation

- 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%*".

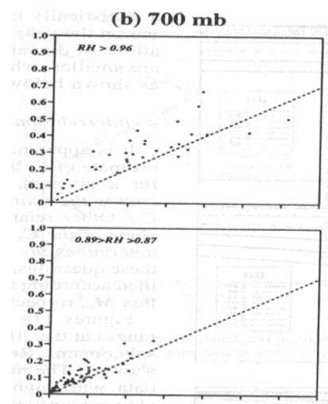
Diagnostic Relative Humidity Schemes

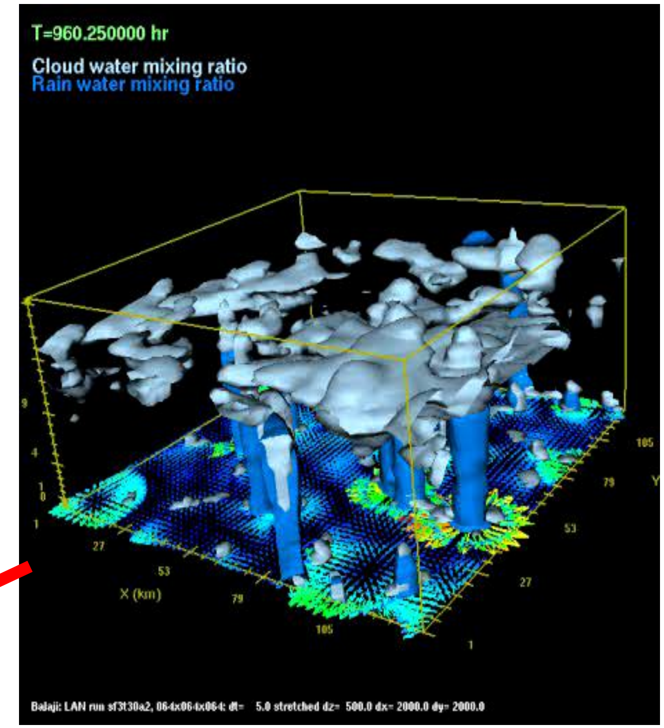
- Advantages:
  - Better than homogeneous assumption, since clouds can form before grids reach saturation.
- Disadvantages:
  - Cloud cover not well coupled to other processes.
  - In reality, different cloud types with different coverage can exist with same relative humidity. This can not be represented.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

$$C = F(RH, q_c)$$





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

Diagnostic Relative Humidity Schemes

- Another example is the scheme of Slingo, operational at ECMWF until 1995.
- This scheme also adds dependence on vertical velocities
- Use different empirical relations for different cloud types, e.g., middle level clouds:

$$C_m = \begin{cases} 0 & \omega \geq 0 \\ C_m^{\ *} \, \omega / \omega_{crit} & \omega_{crit} \leq \omega < 0 \\ C_m^{\ *} & \omega < \omega_{crit} \end{cases} \qquad C_m^{\ *} = \left[\max\left(\frac{RH - RH_{crit}}{1 - RH_{crit}}, 0 \right) \right]^2$$

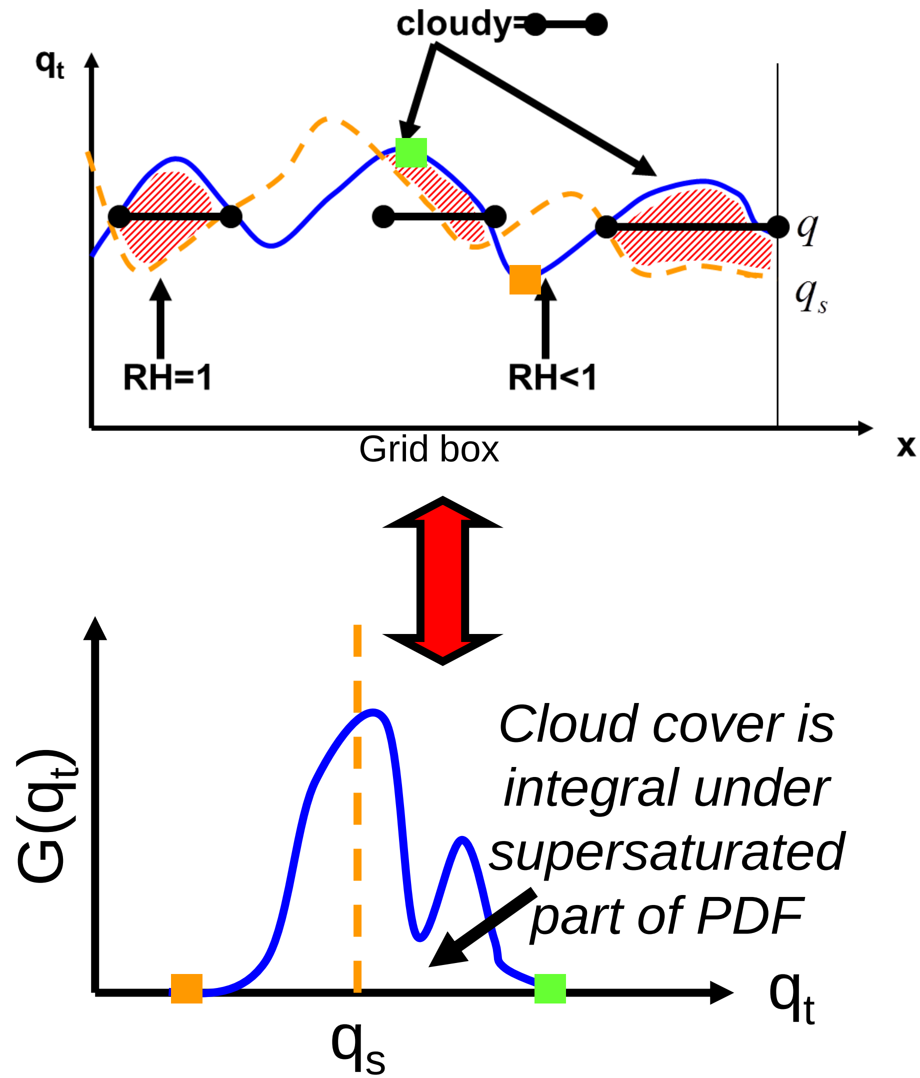
Relationships seem Ad-hoc? Can we do better?

Statistical PDF Schemes

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

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

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



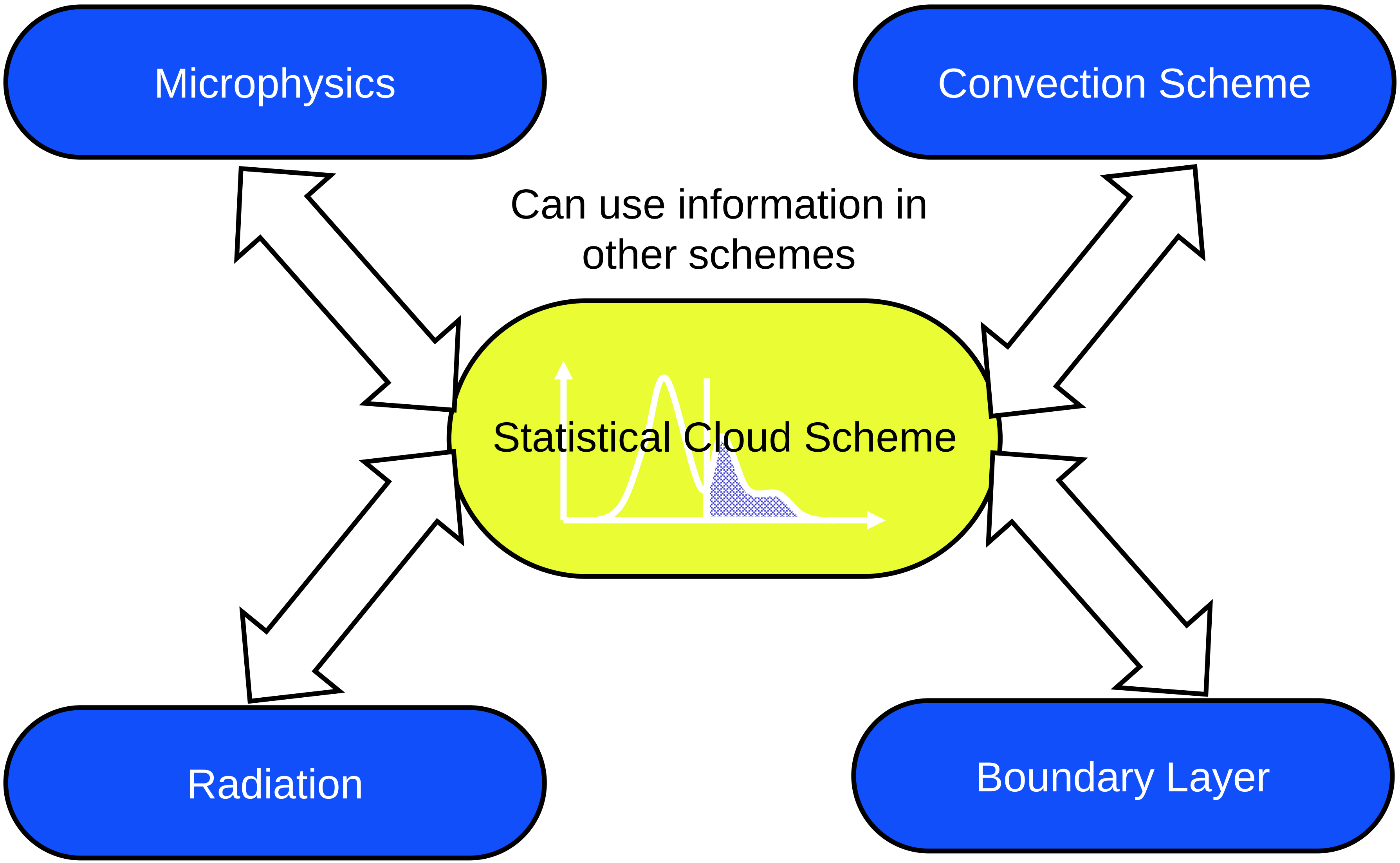
Sommeria and Deardorff (1977), Mellor (1977)

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

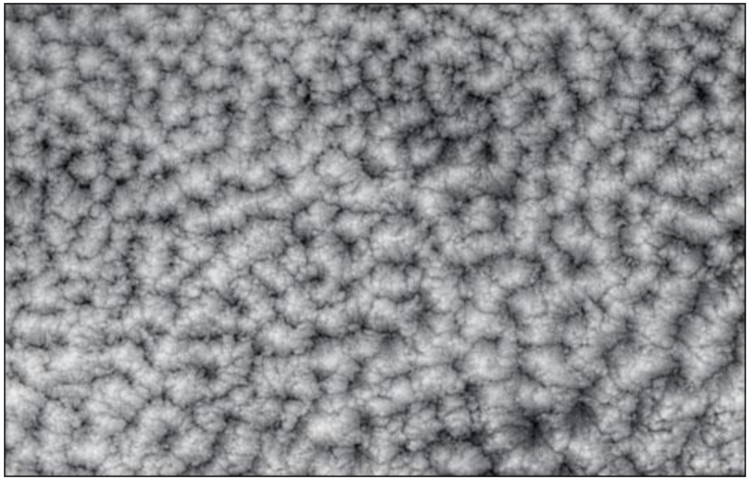


Building a statistical cloud scheme

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?

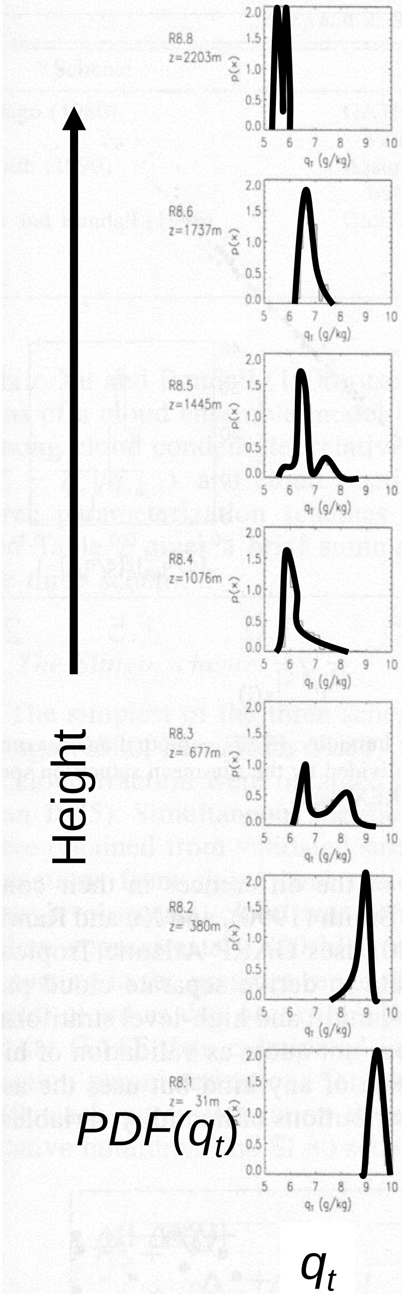


FIG. 2. Distributions of total water fr
penetrative cumulus during A

Wood and Field
JAS 2000
Aircraft
observations low
clouds < 2km

Aircraft Observed PDFs

Heymsfield and
McFarquhar
JAS 96
Aircraft IWC obs
during CEPEX

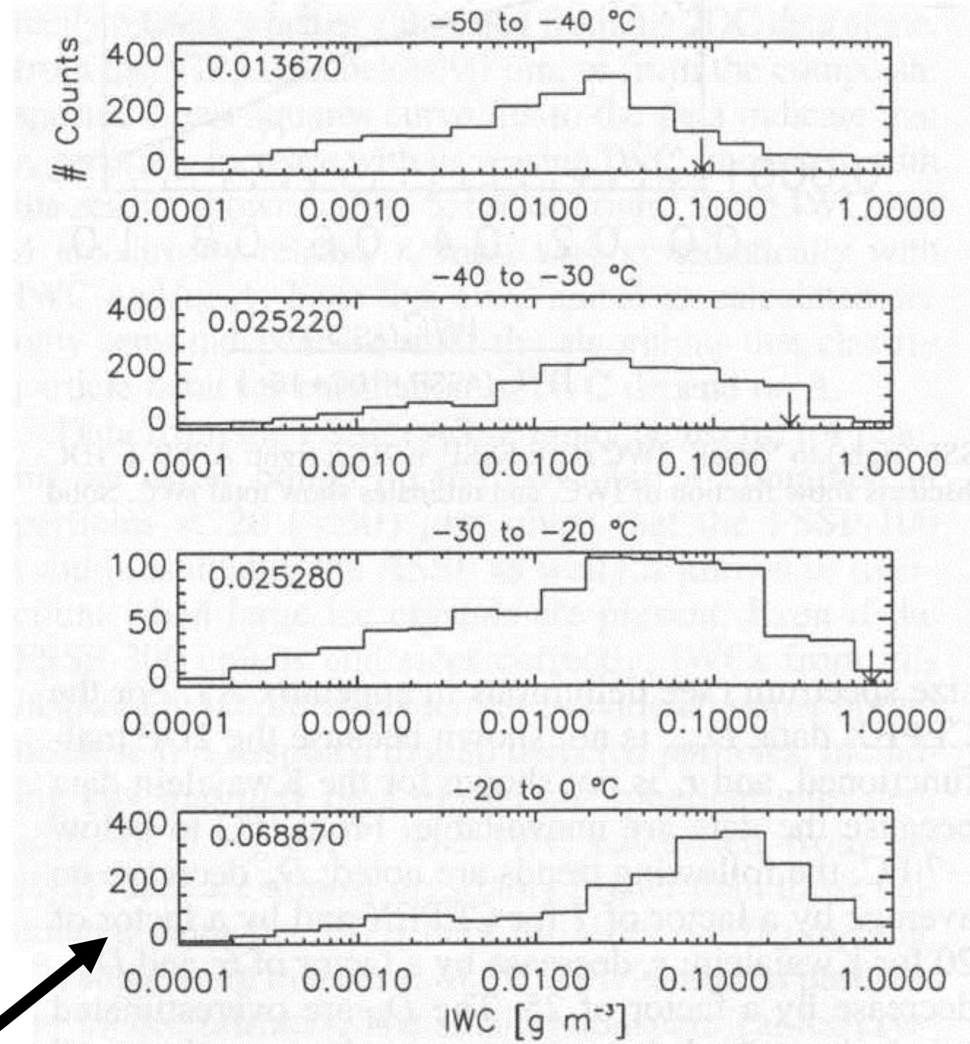
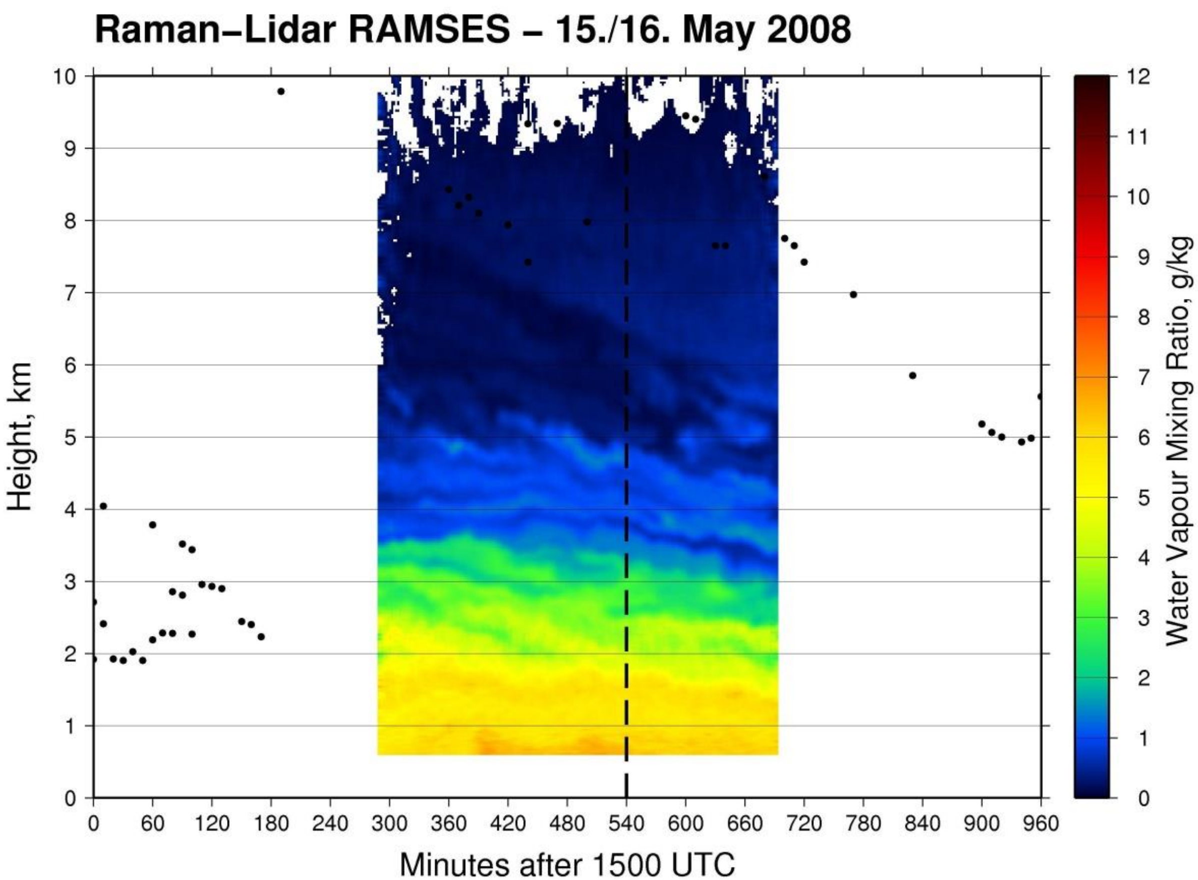
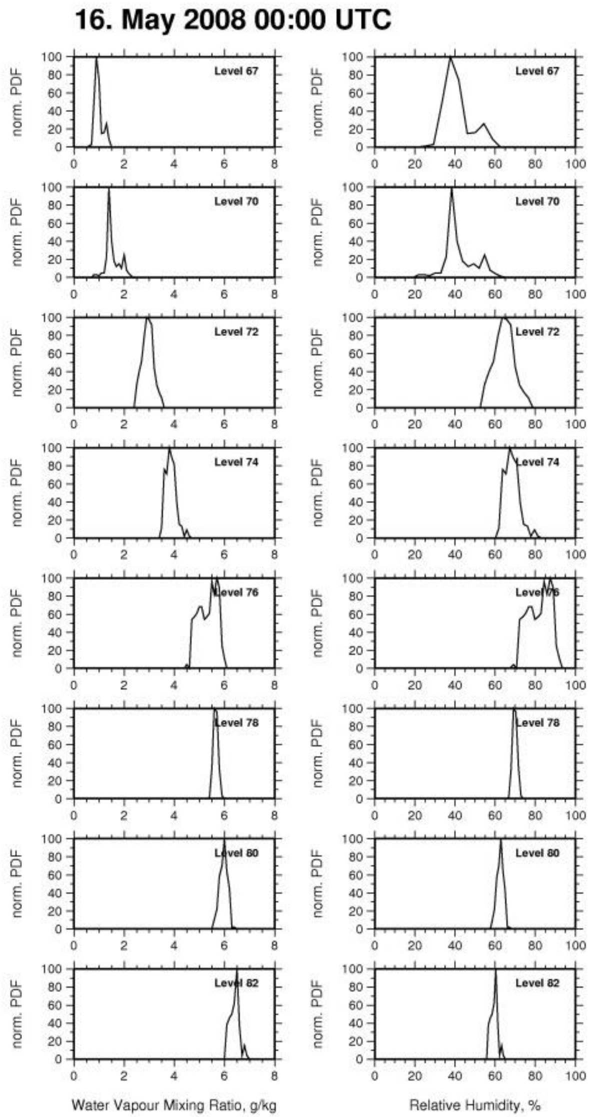


FIG. 9. Frequency distributions of IWC sorted by temperature from 2DC data during CEPEX. Each count (ordinate) represents 10-s average. Median IWC (g m^{-3}) in upper left corner of each panel. Arrows give saturation vapor density with respect to ice for midpoint of each temperature interval.

Building a statistical cloud scheme
Observed PDF of water vapour/RH Raman Lidar





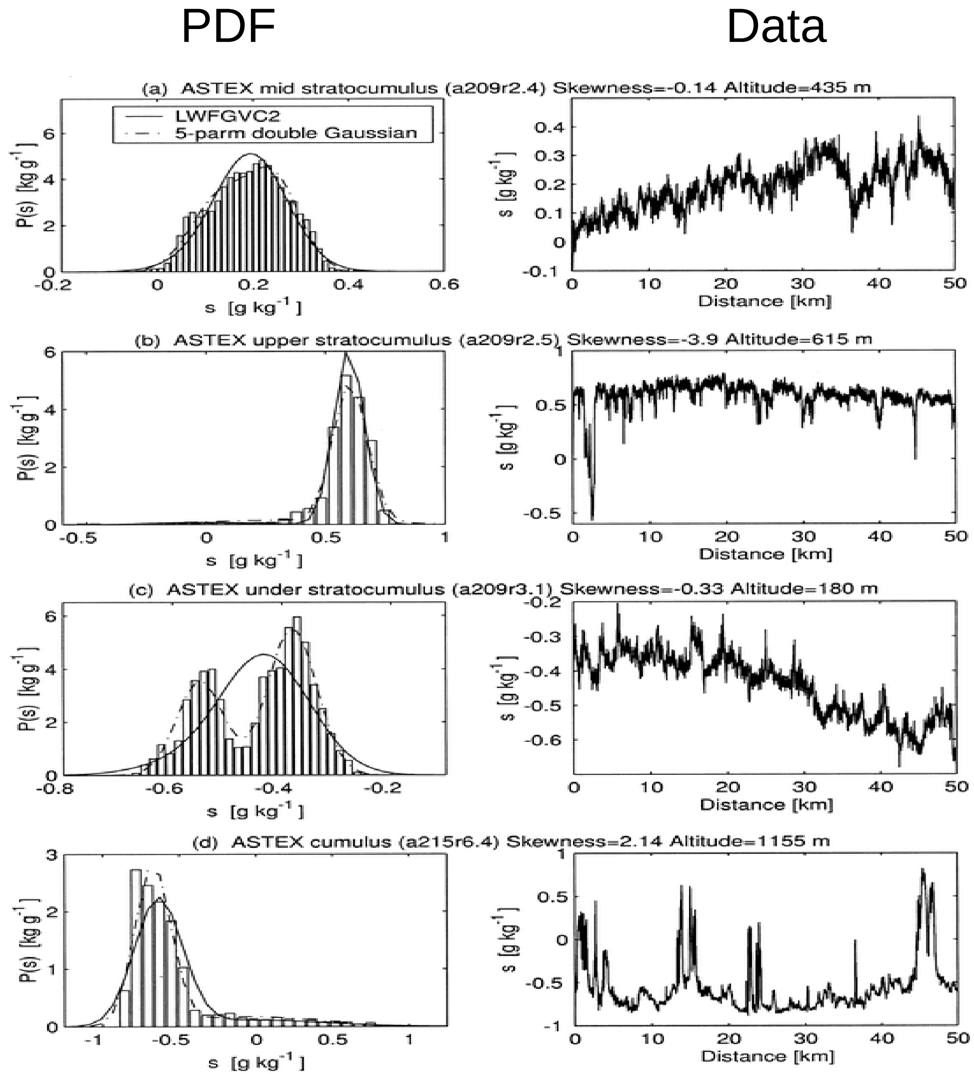
From Franz Berger

Building a statistical cloud scheme

Observed PDF example from aircraft

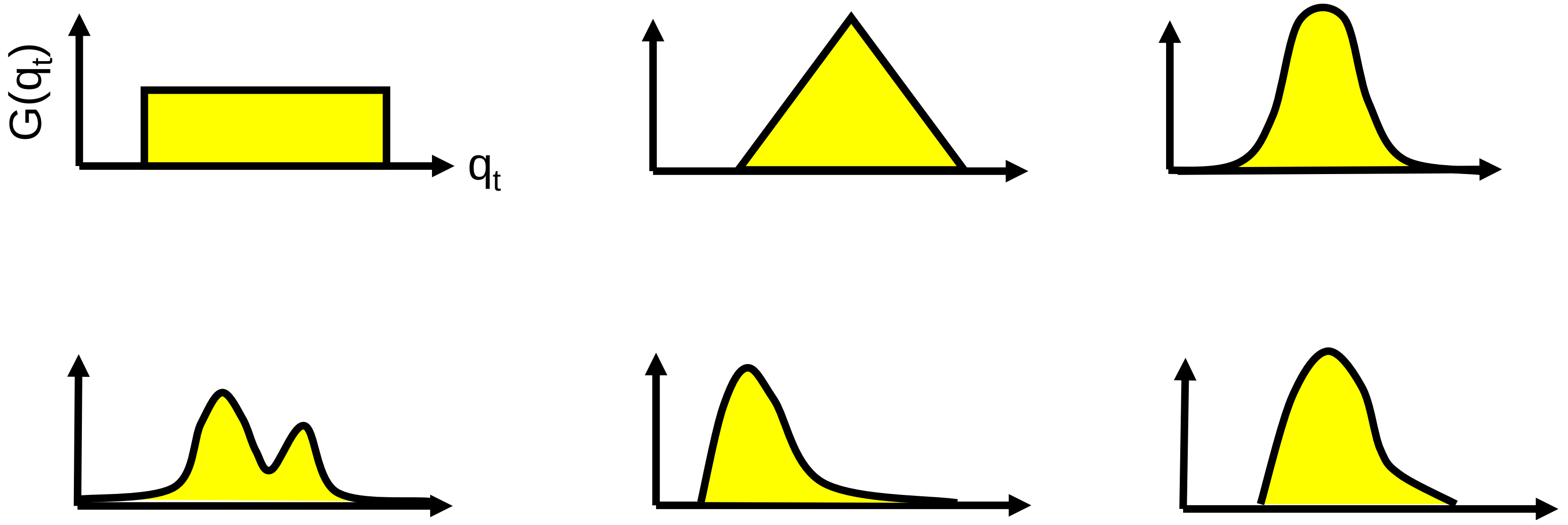
Example, aircraft data from Larson et al. 01/02

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



Building a statistical cloud scheme

- 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?)

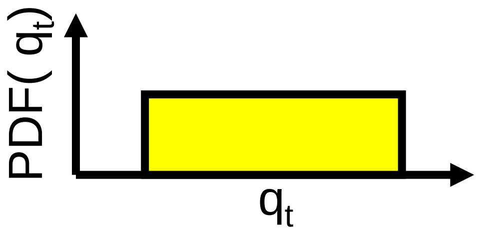


Building a statistical cloud scheme

(1) Specification of PDF shape

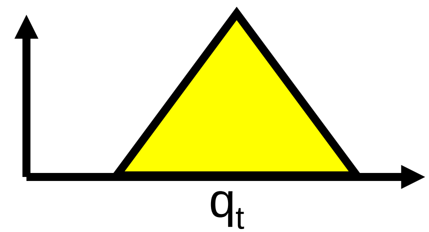
Many function forms have been used

symmetrical distributions:



Uniform:

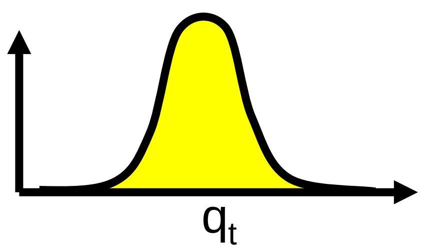
Letreut and Li (91)



Triangular:

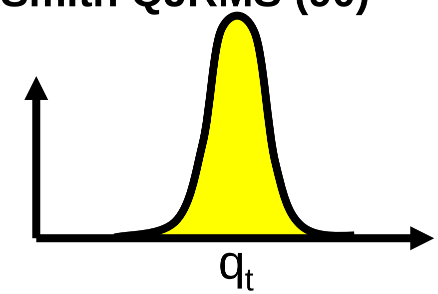
Smith QJRMS (90)

Bounded



Gaussian:

Mellor JAS (77)



s^4 polynomial:

Lohmann et al. J. Clim (99)

Unbounded:

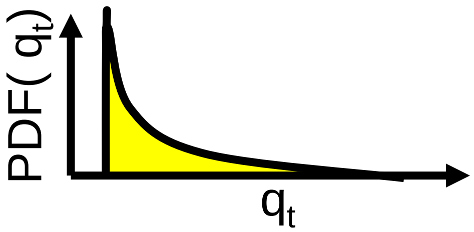
Can clip, but need additional parameters

Building a statistical cloud scheme

(1) Specification of PDF shape

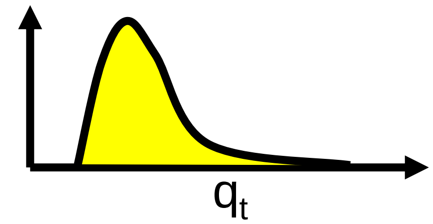
skewed distributions:

Unbounded, always skewed



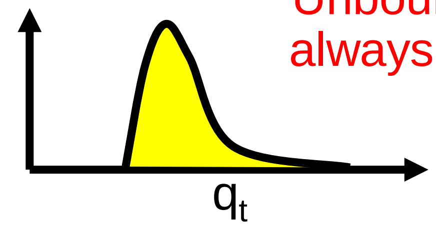
Exponential:

Sommeria and Deardorff JAS (77)



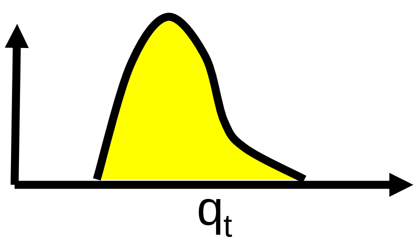
Lognormal:

Bony & Emanuel JAS (01)



Gamma:

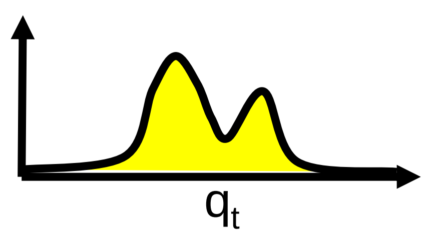
Barker et al. JAS (96)



Beta:

Tompkins JAS (02)

Bounded, symmetrical or skewed



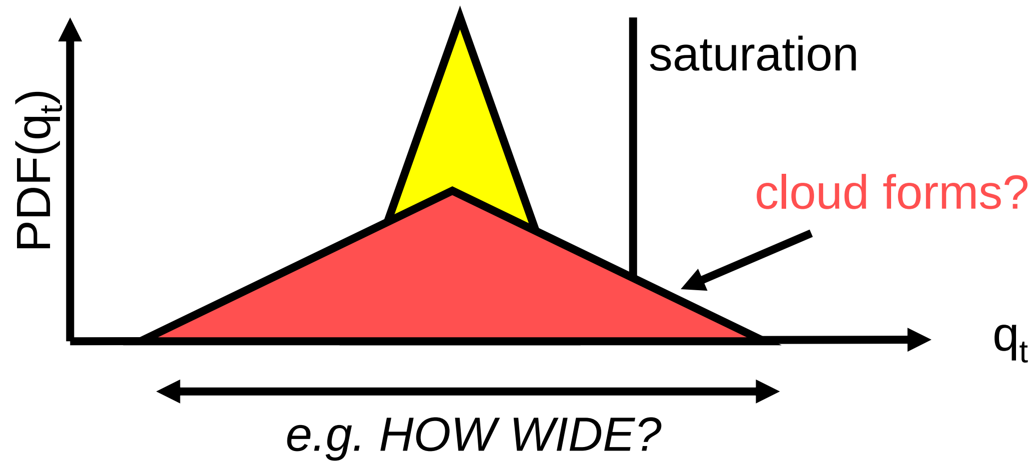
Double Normal/Gaussian:

Lewellen and Yoh JAS (93), Golaz et al. JAS 2002

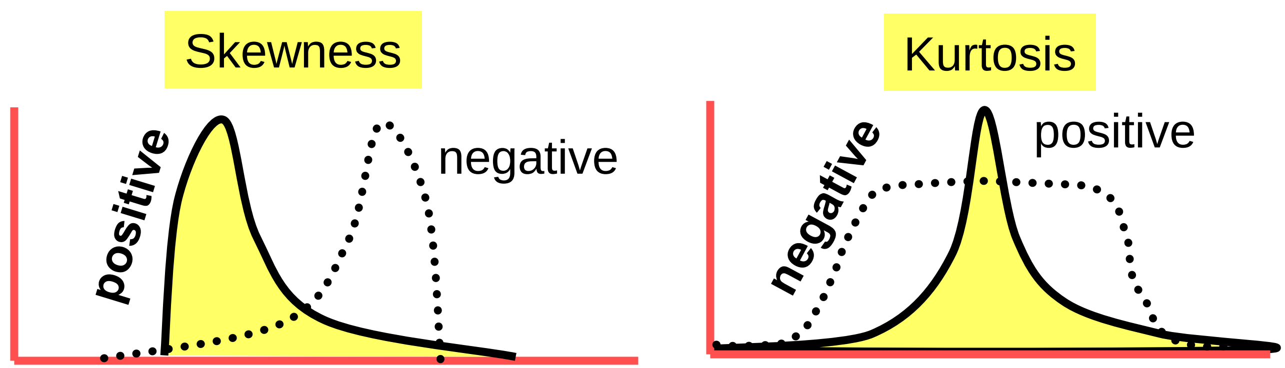
Building a statistical cloud scheme
(2) Specification of PDF moments

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

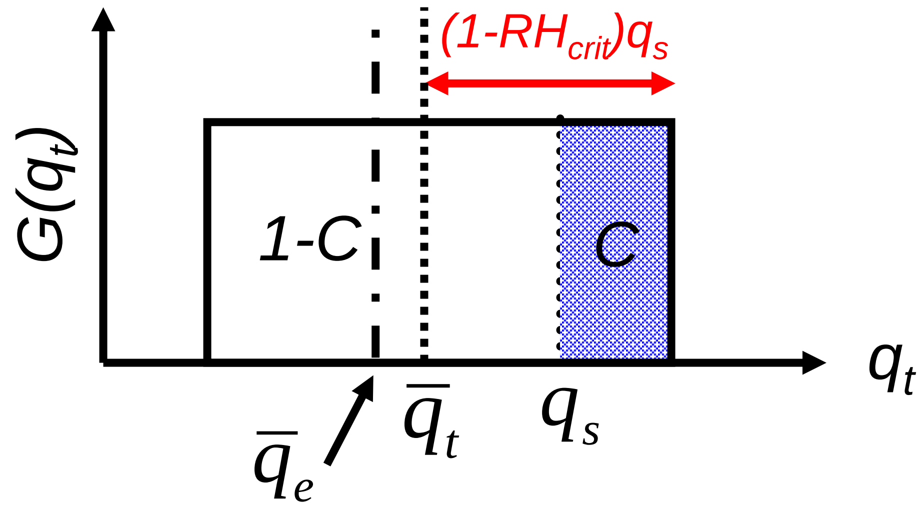


Functional form – needs to fit data but be sufficiently simple

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



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

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

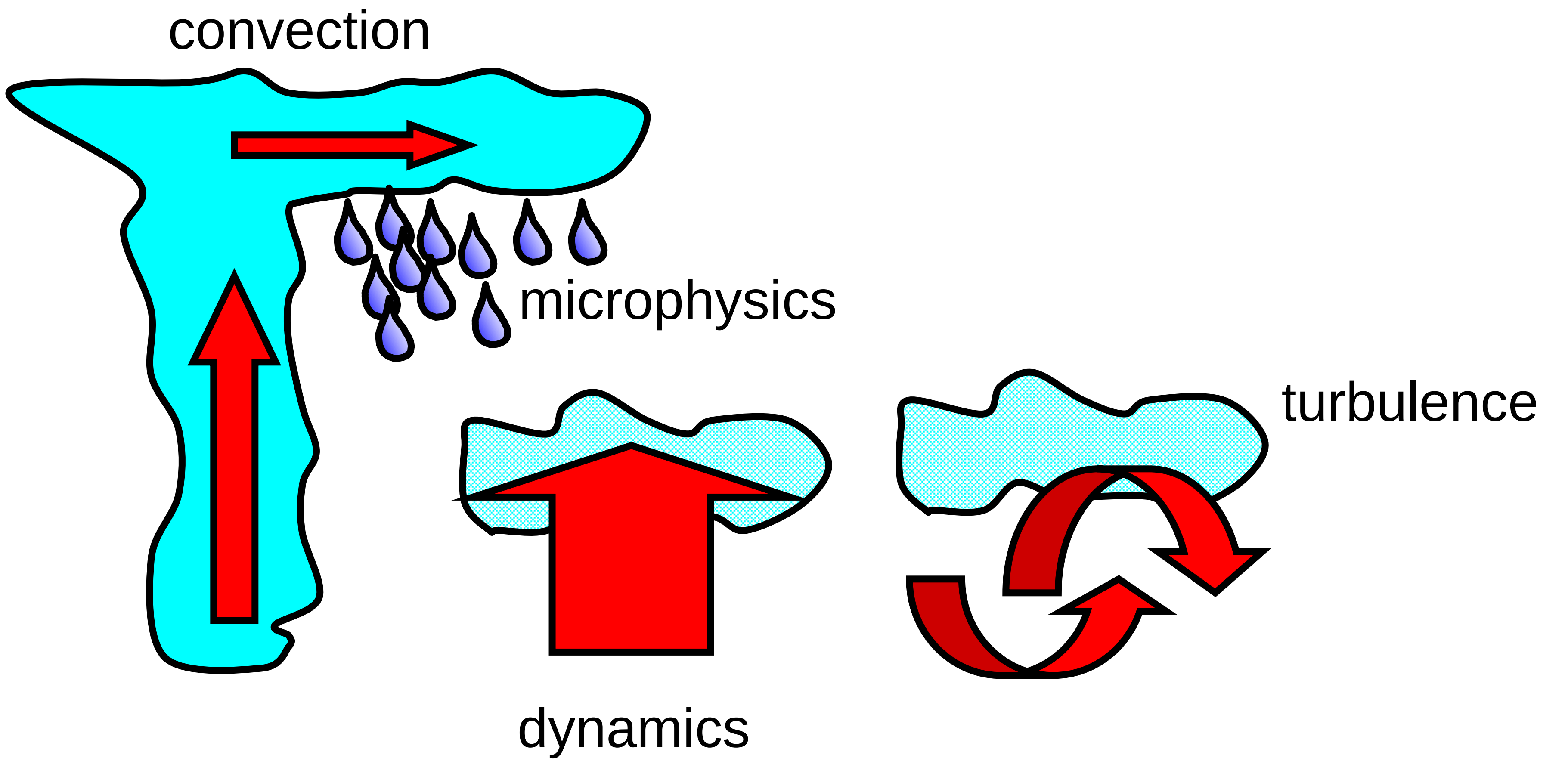
$$RH = \frac{\overline{q}_v}{q_s} = 1-(1-RH_{crit})(1-C)^2$$

Sundqvist formulation!!!

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

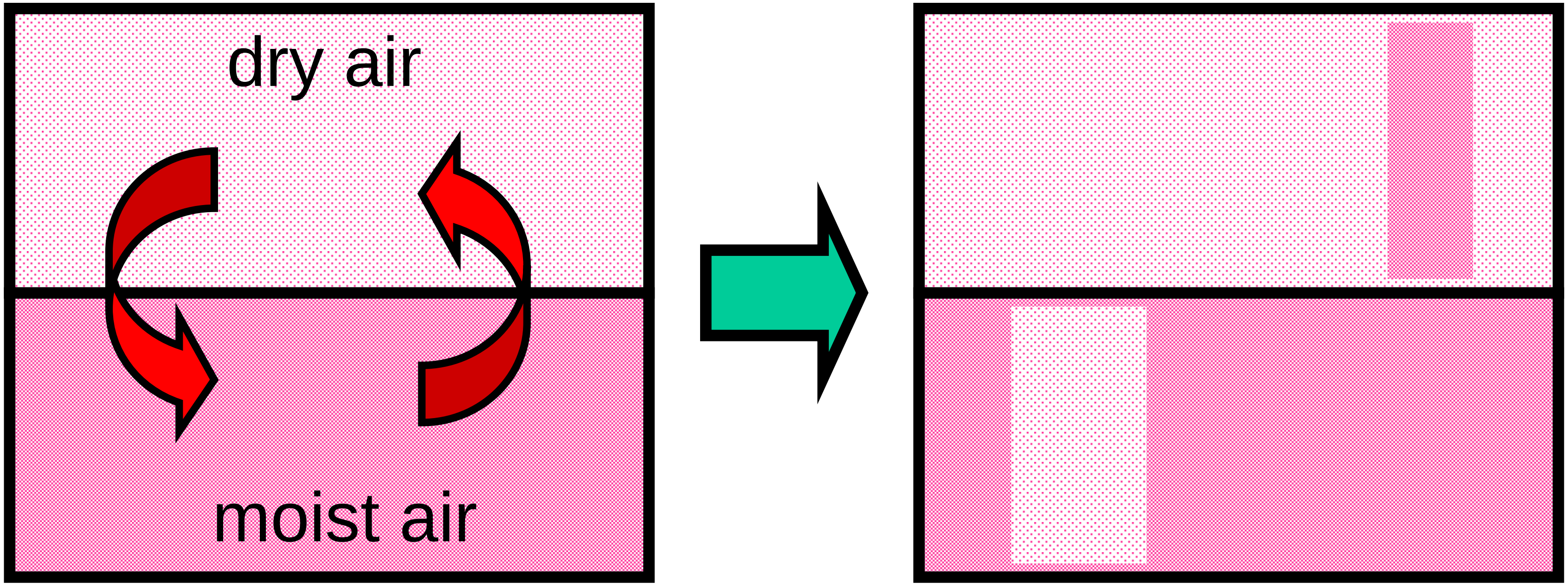
Building a statistical cloud scheme

Processes that can affect PDF moments



Example: Turbulence

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

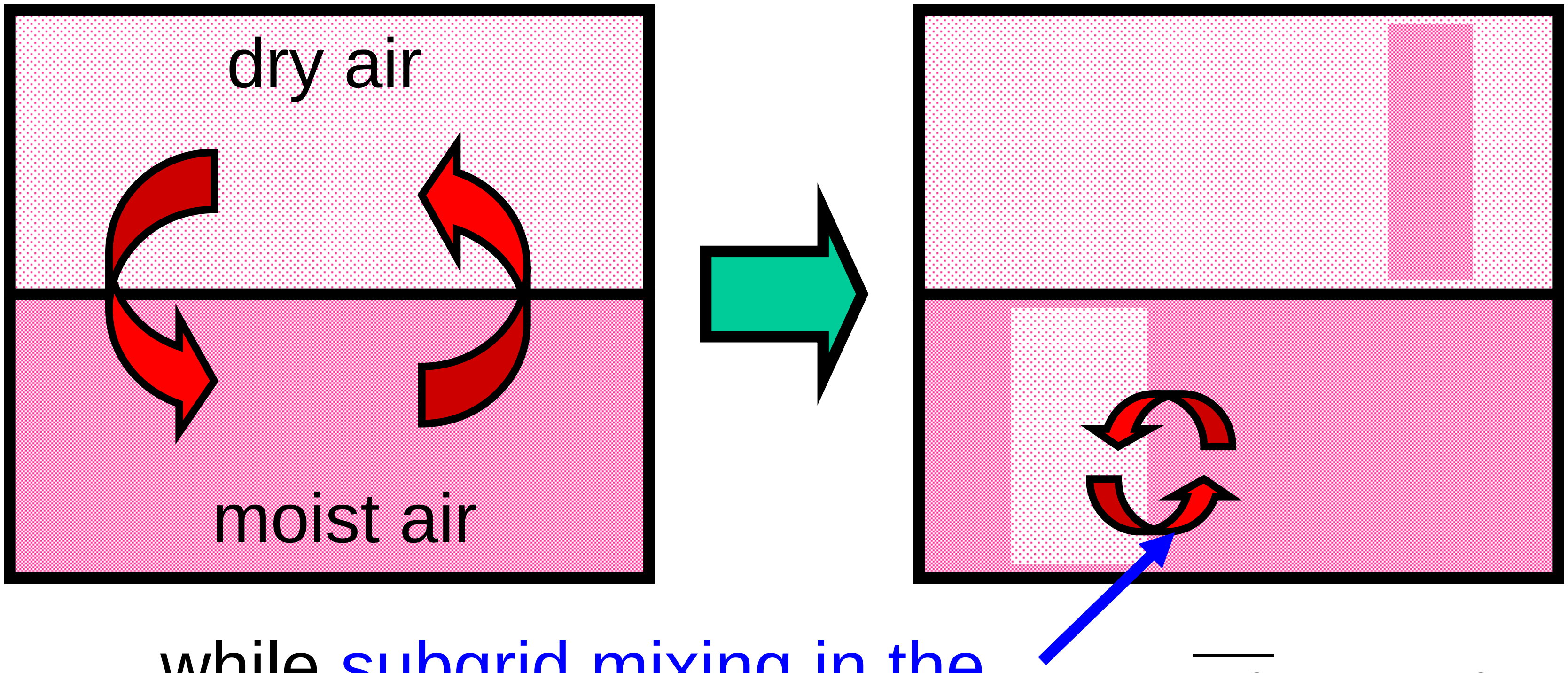


Rate of change of total water variance

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

Example: Turbulence

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



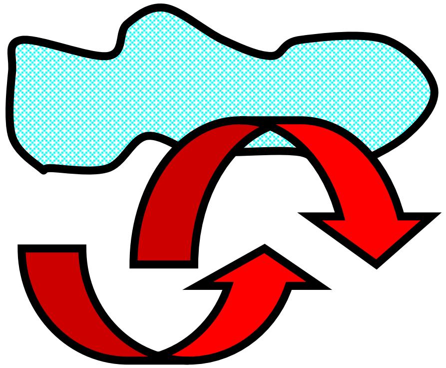
while subgrid mixing in the horizontal plane naturally reduces the horizontal variability

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

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

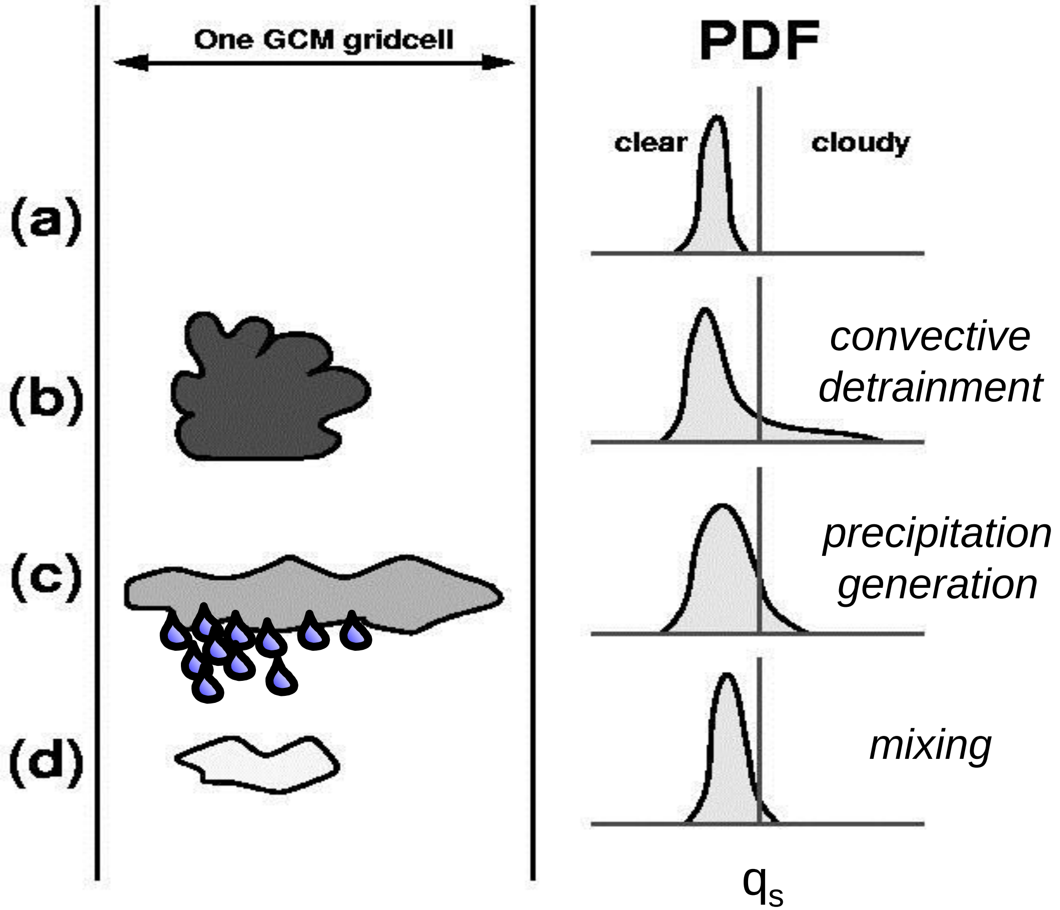
Example: Ricard and Royer, Ann Geophy, (93), Lohmann et al. J. Clim (99)

- 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

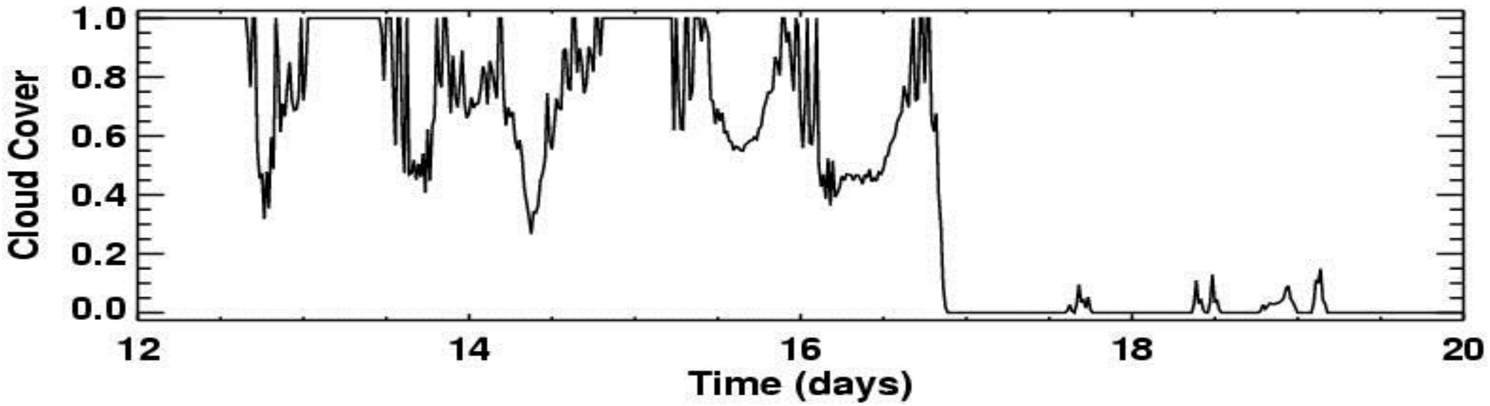
Example: Tompkins (2002) prognostic PDF

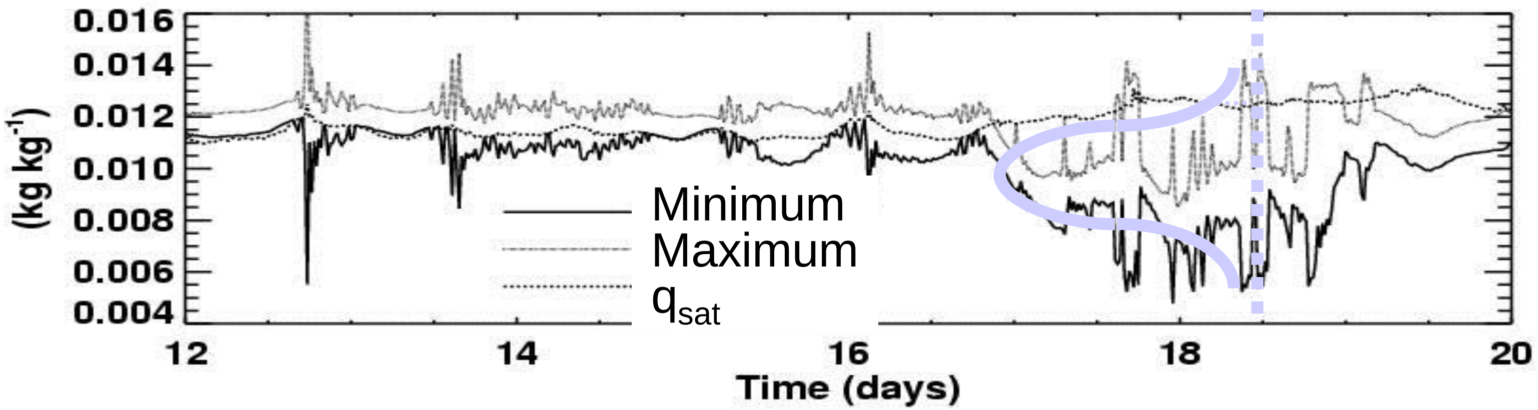
- Tompkins (2002) prognostic statistical scheme (implemented in ECHAM5 climate GCM).
- Prognostic equations are introduced for variables representing the mean, variance and skewness of the total water PDF.
- Some of the sources and sinks are rather ad-hoc in their derivation!



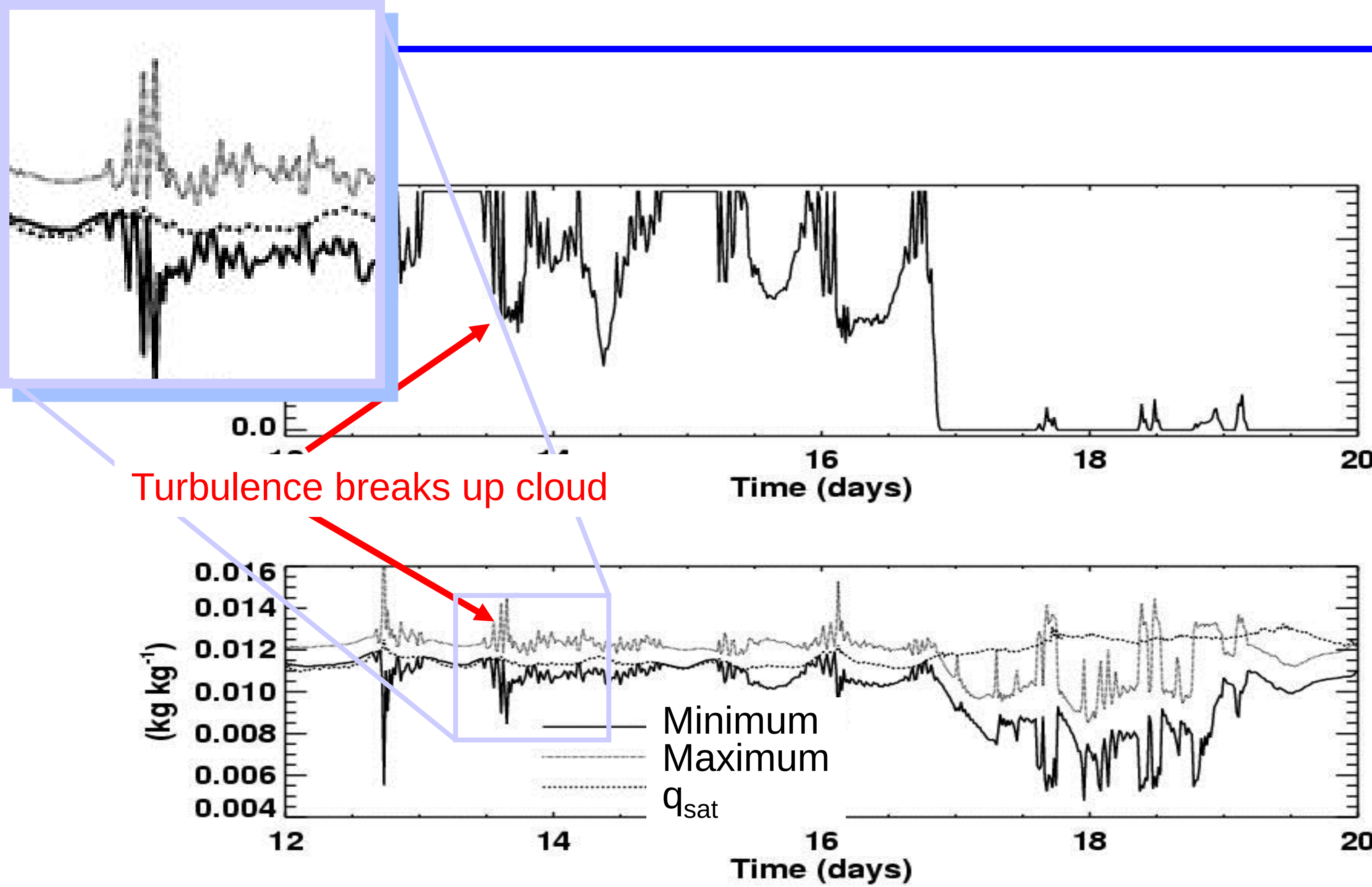
Prognostic statistical scheme in action

Evolution of stratocumulus cloud – Tompkins (2002)

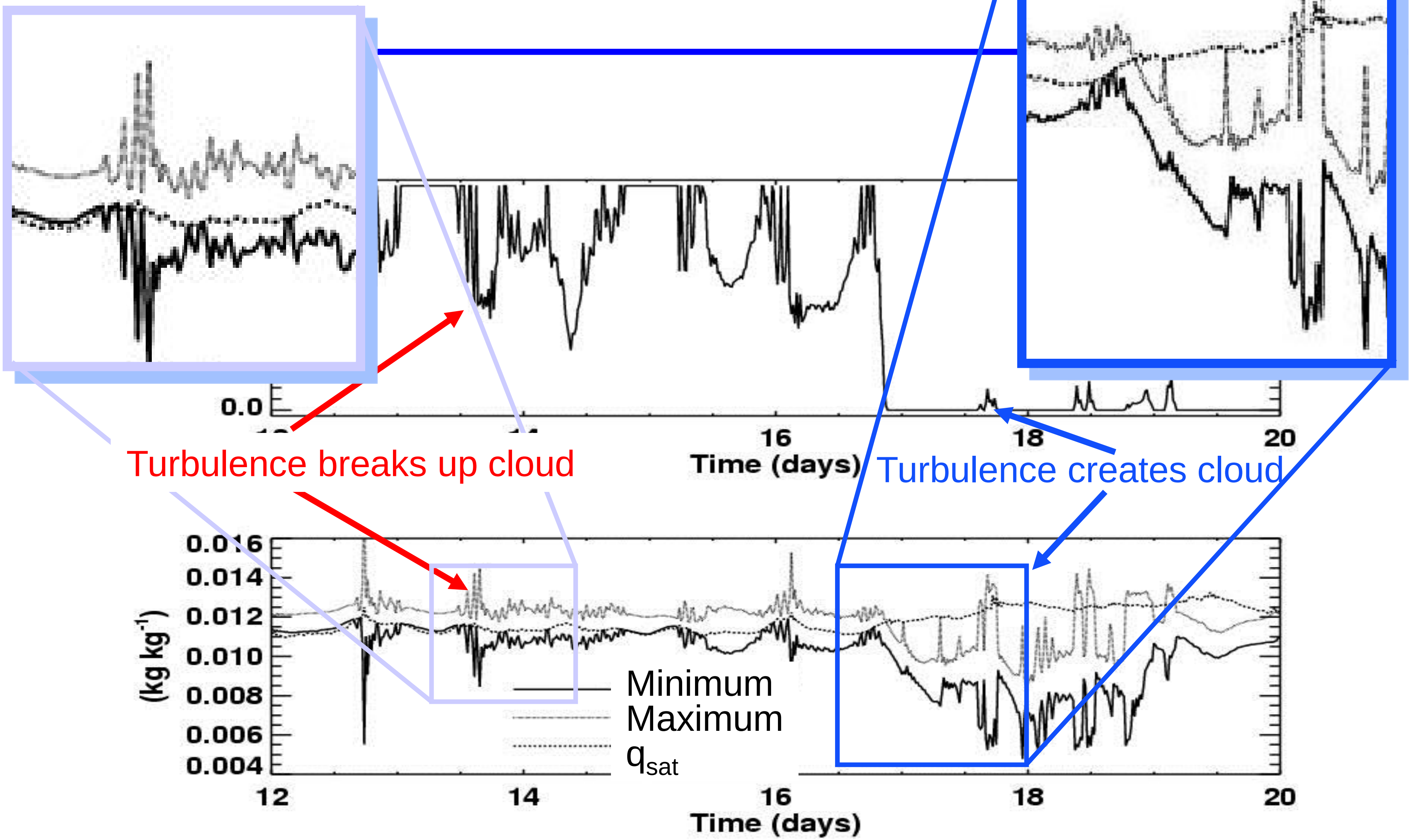




Prognostic Statistical Scheme in action



Prognostic Statistical Scheme in action

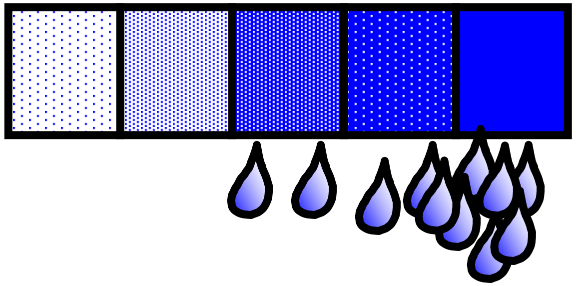


Building a statistical cloud scheme

Predicting change of q_t variance due to precipitation

- Change in variance due to precipitation

$$\frac{d\overline{q_t'^2}}{dt} = \overline{P'q_t'} = \int_{q_t=q_{sat}}^{q_{t\_max}} P'q_t'G(q_t)dq_t$$



Where *P* is the precipitation generation rate, e.g:

$$P = Kq_l(1-e^{-(\frac{ql}{qlcrit})^2})$$

- However, the tractability depends on the PDF form for the subgrid fluctuations of q_t, given by *G*.

Some further issues for GCMs

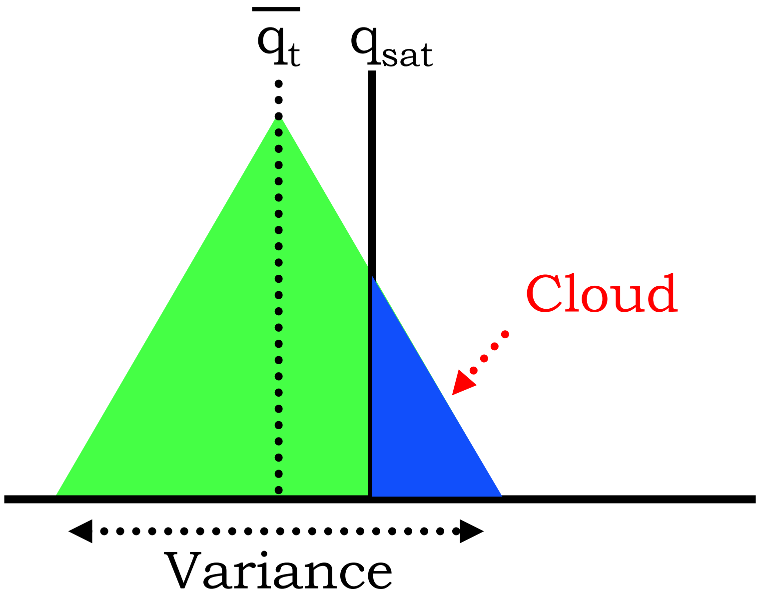
- **If we assume a 2-parameter PDF for total water, which prognostic variables should we use ?**
- How do we treat the ice phase when supersaturation is allowed ?
- How do we treat sedimentation ?

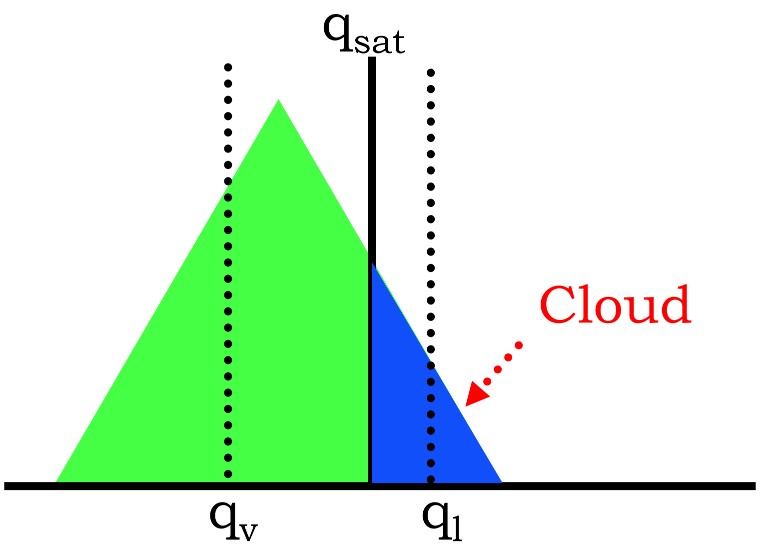
Prognostic statistical PDF scheme:
Which prognostic variables/equations?

Take a 2 parameter distribution & partially cloudy conditions

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

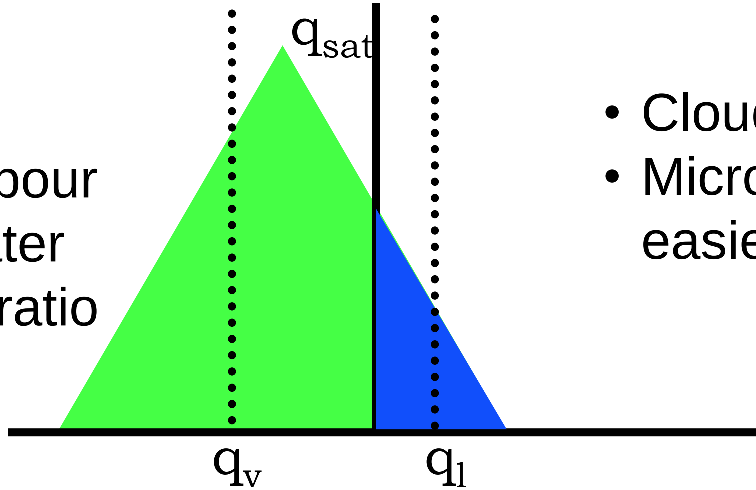
(2) Can specify distribution with
  (a) Water vapour
  (b) Cloud water mass mixing ratio





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

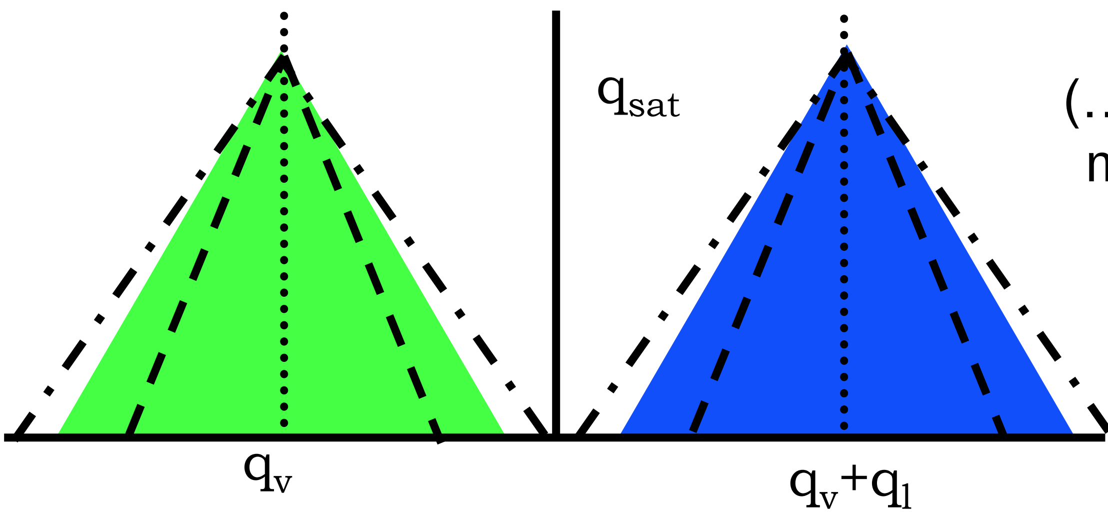
(a) Water vapour
(b) Cloud water
mass mixing ratio



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

But problems arise in...

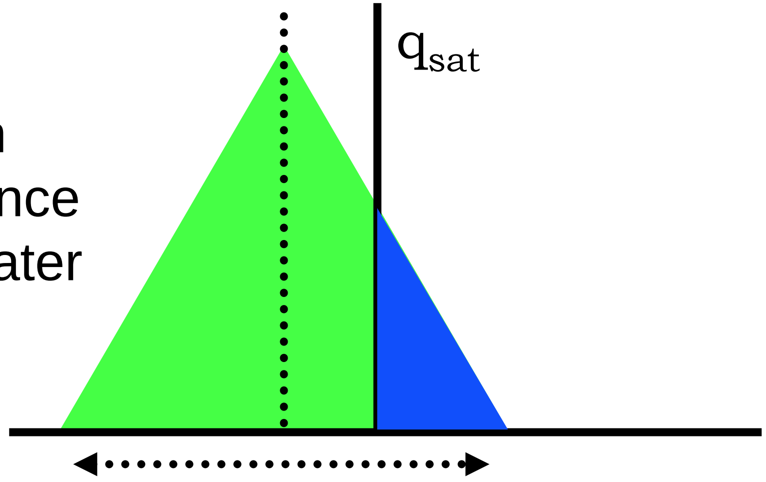
Clear sky conditions (turbulence)



Overcast conditions (…convection + microphysics)

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)
- Need to parametrize those tricky microphysics terms!

Some further issues for GCMs

- If we assume a 2-parameter PDF for total water, which prognostic variables should we use ?

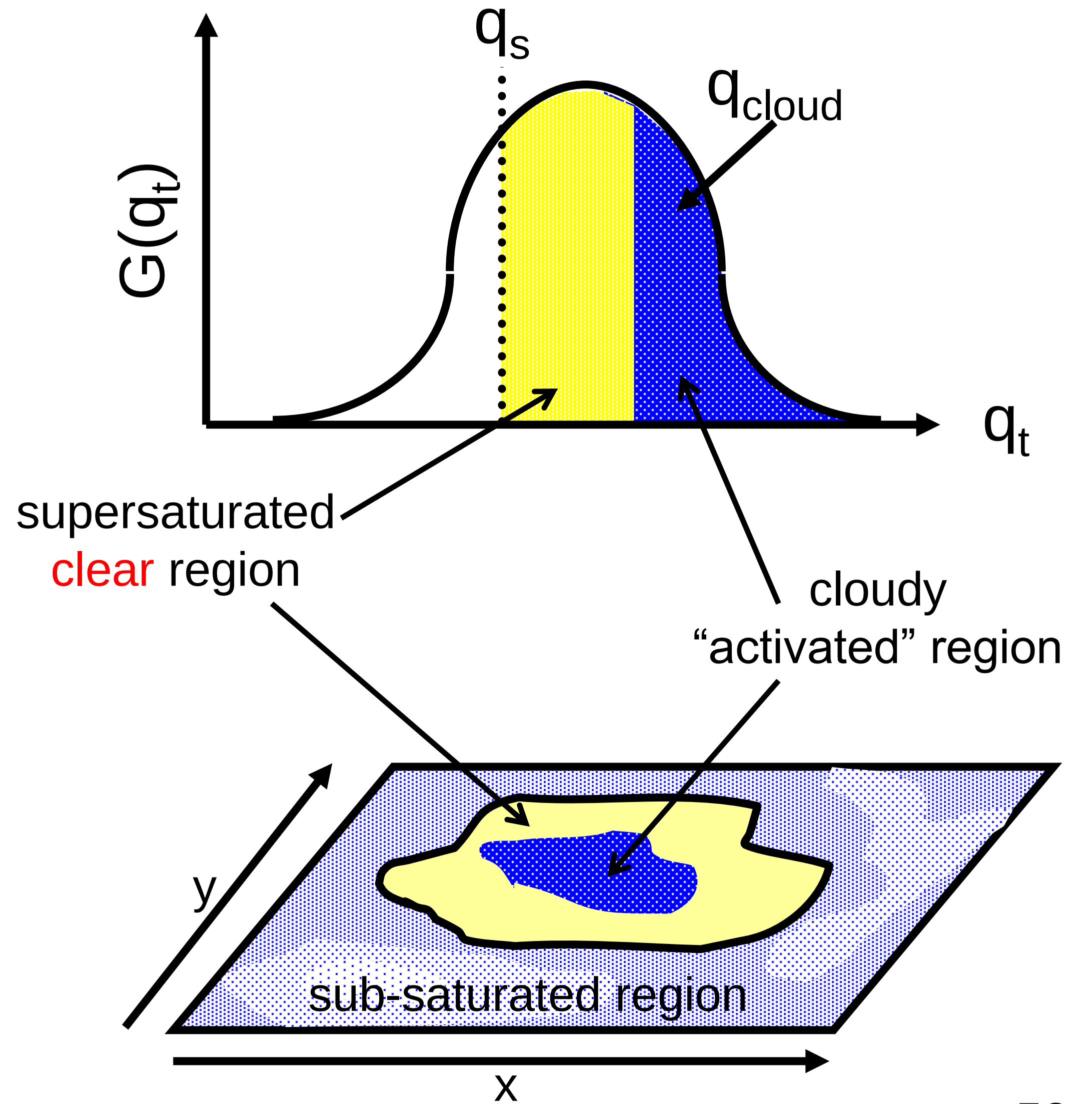
- **How do we treat the ice phase when supersaturation is allowed ?**

- How do we treat sedimentation ?

Prognostic statistical PDF scheme:
How do we treat ice (and mixed-phase) cloud?

If supersaturation allowed, then the equation for cloud-ice no longer holds

$$q_i \neq \int_{q_s}^{\infty} (q_t - q_s) G(q_t) dq_t$$



Some further issues for GCMs

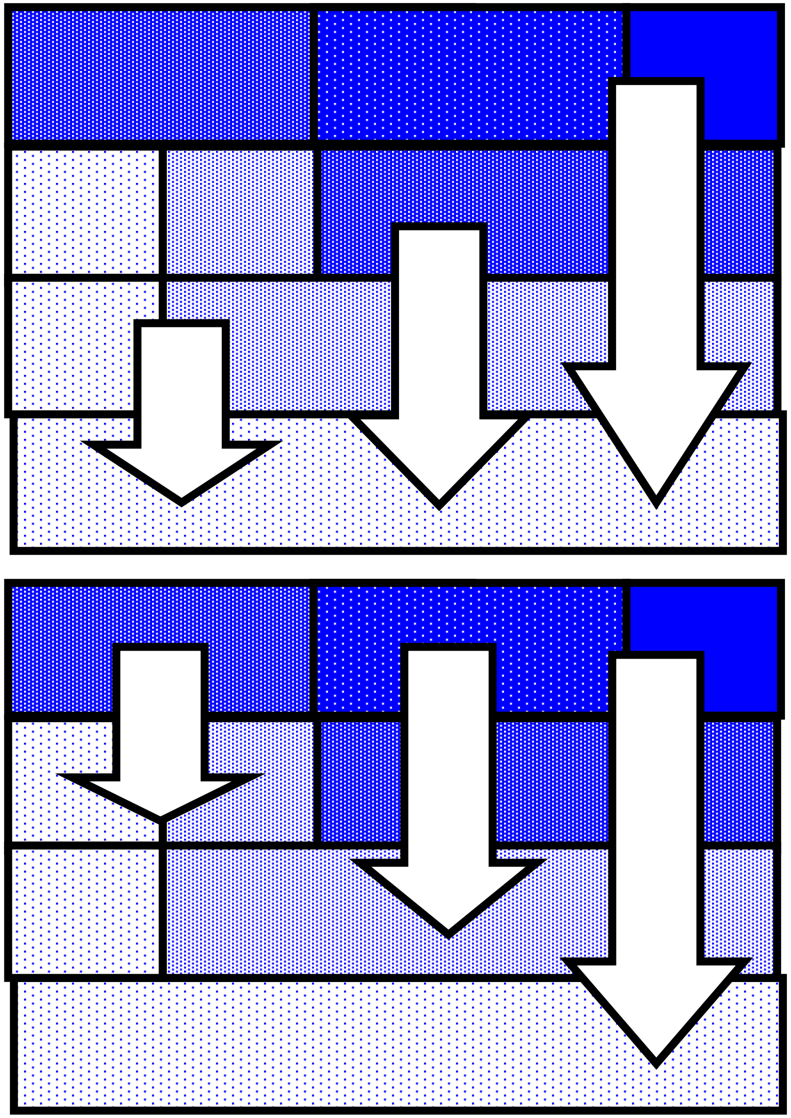
- If we assume a 2-parameter PDF for total water, which prognostic variables should we use ?
- How do we treat the ice phase when supersaturation is allowed ?
- **How do we treat sedimentation ?**

Prognostic statistical PDF scheme:

How do we treat sedimentation ?

Can quickly get untractable !

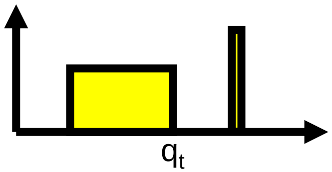
- E.g: Semi-Lagrangian ice sedimentation
- Source of variance is far from simple, also depends on overlap assumptions
- Would really also like to retain the sub-flux variability too



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!

Sub-grid cloud parametrization
Current status in GCMs…?



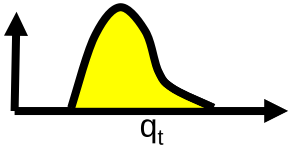
Uniform-delta:
Tiedtke (1993)

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

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

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

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



Beta:
Tompkins (2002)

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.

References

Larson, V. E., R. Wood, P. R. Field, J.-C. Golaz, T. H. Vonder Haar, and W. R. Cotton, (2001). Small-Scale and Mesoscale Variability of Scalars in Cloudy Boundary Layers: One-Dimensional Probability Density Functions. *J. Atmos. Sci*., **58**, 1978-1994

Sundqvist, H. Berge, E., Kristjansson, J. E., 1989: Condensation and cloud parametrization studies with a mesoscale numerical weather prediction model. *Mon. Wea. Rev*., **177**, 1641-1657.

Tompkins, A. M., (2002). A prognostic parametrization for the subgrid-scale variability of water vapor and clouds in large-scale models and its use to diagnose cloud cover. *J. Atmos. Sci*., **59**, 1917-1942.

Wood, R., Field, P. R., (2000). Relationships between total water, condensed water and cloud fraction in stratiform clouds examinied using aircraft data. *J. Atmos. Sci*., **57**, 1888-1905.

Xu, K. M., and D. A. Randall, (1996). A semi-empirical cloudiness parameterization for use in climate models. *J. Atmos. Sci*., **53**, 3084-3102.