Cloud Parameterization

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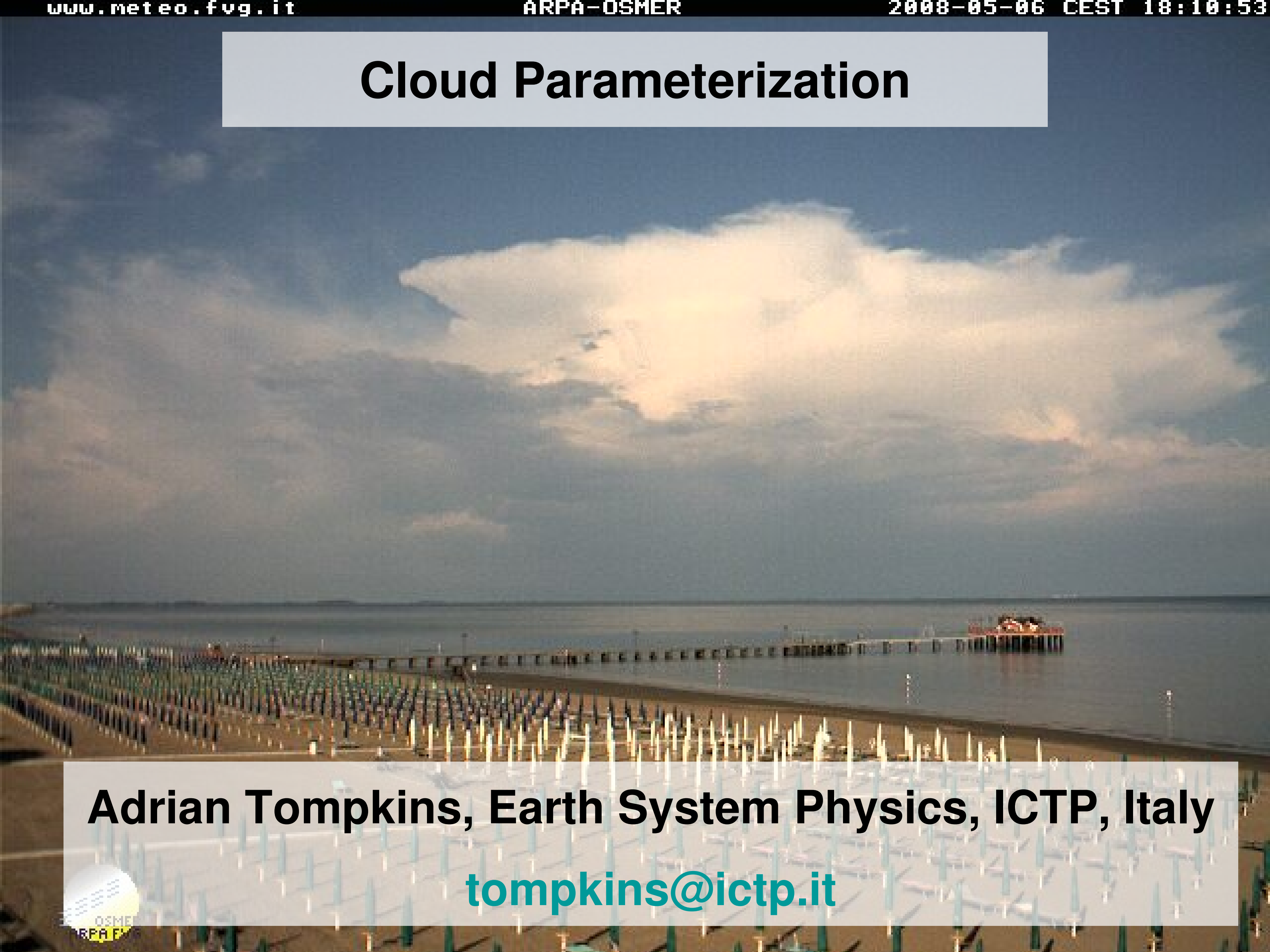
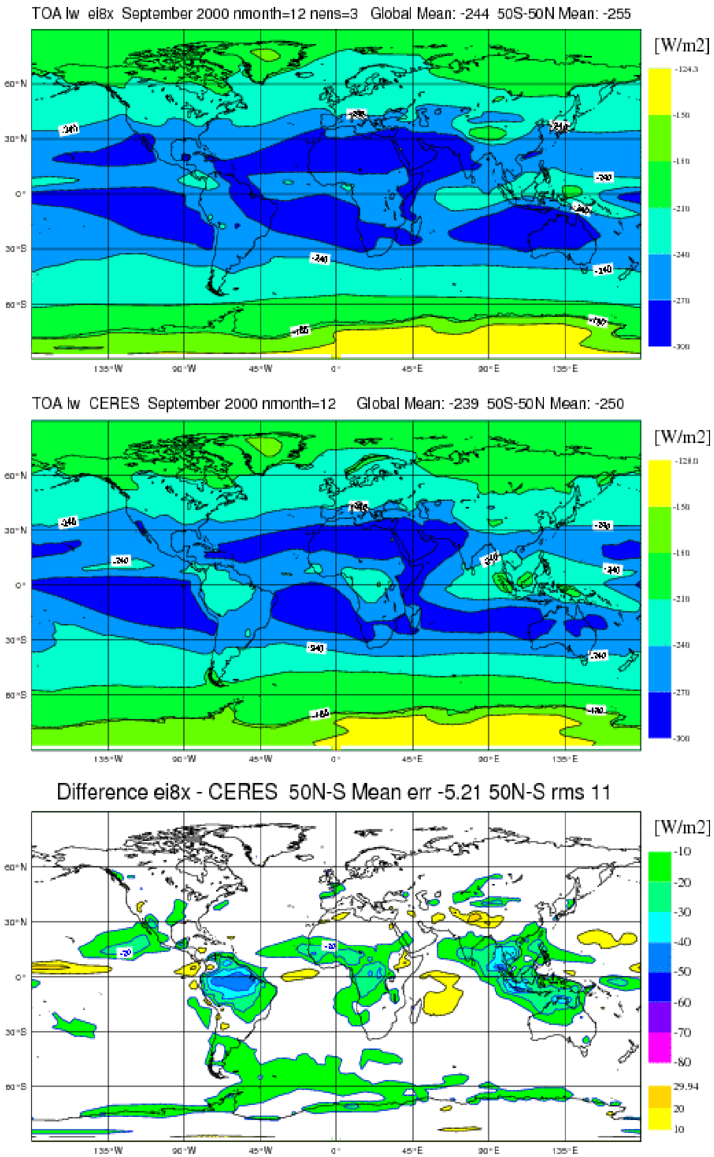


Motivation for whole seminar series: ECMWF climate run top of atmos infra-red errors compared to CERES

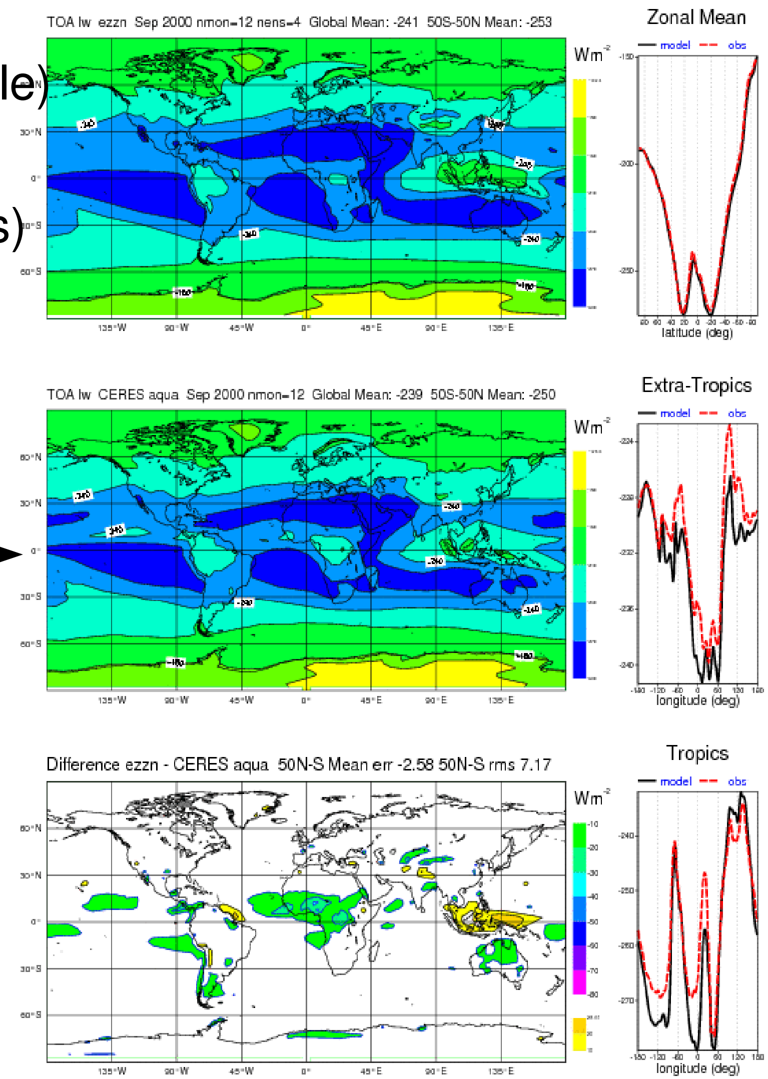


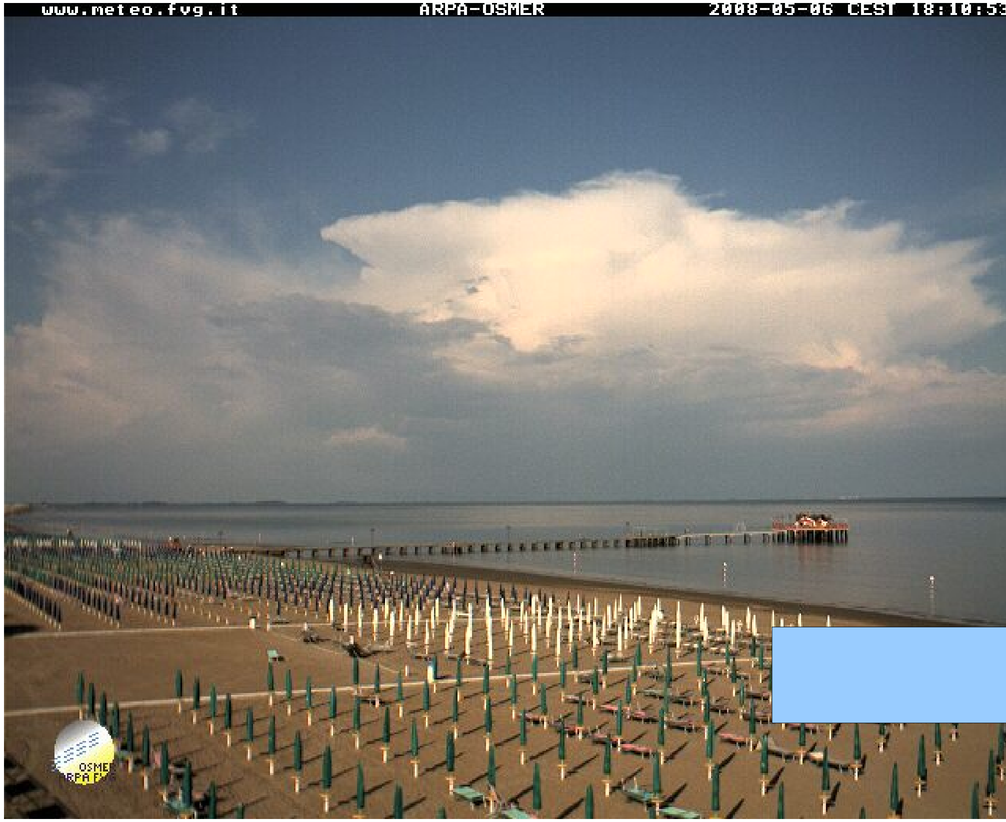
23r4 (ERA40 cycle)

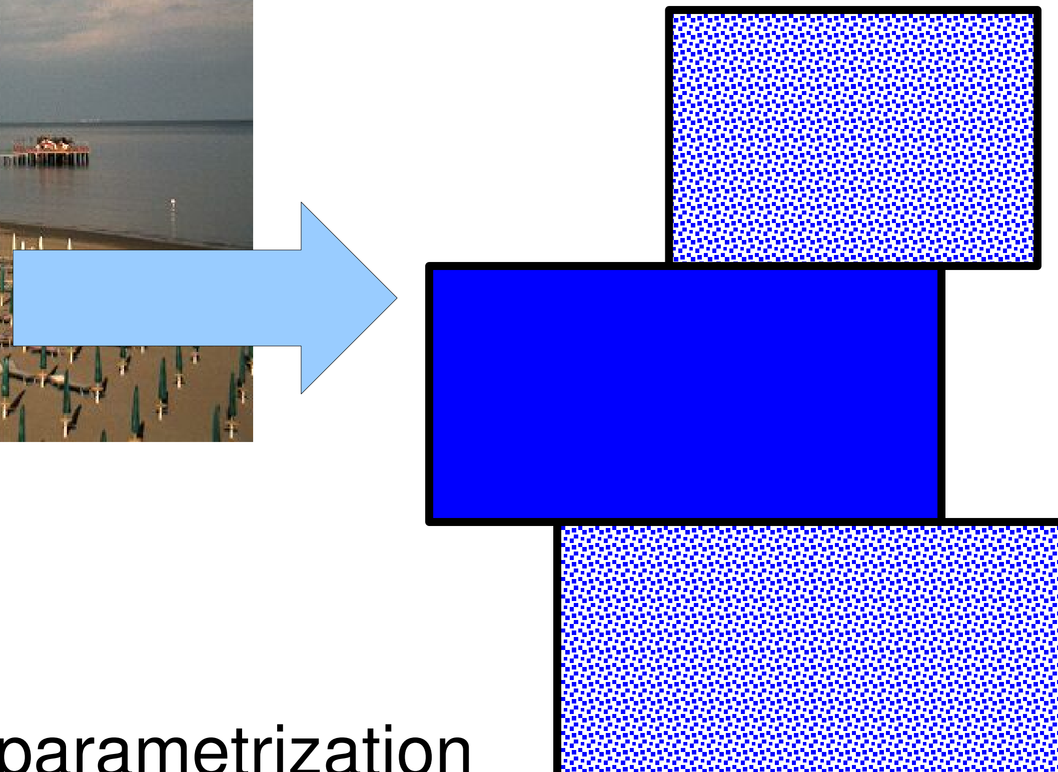
33r1 (operations)

CERES obs

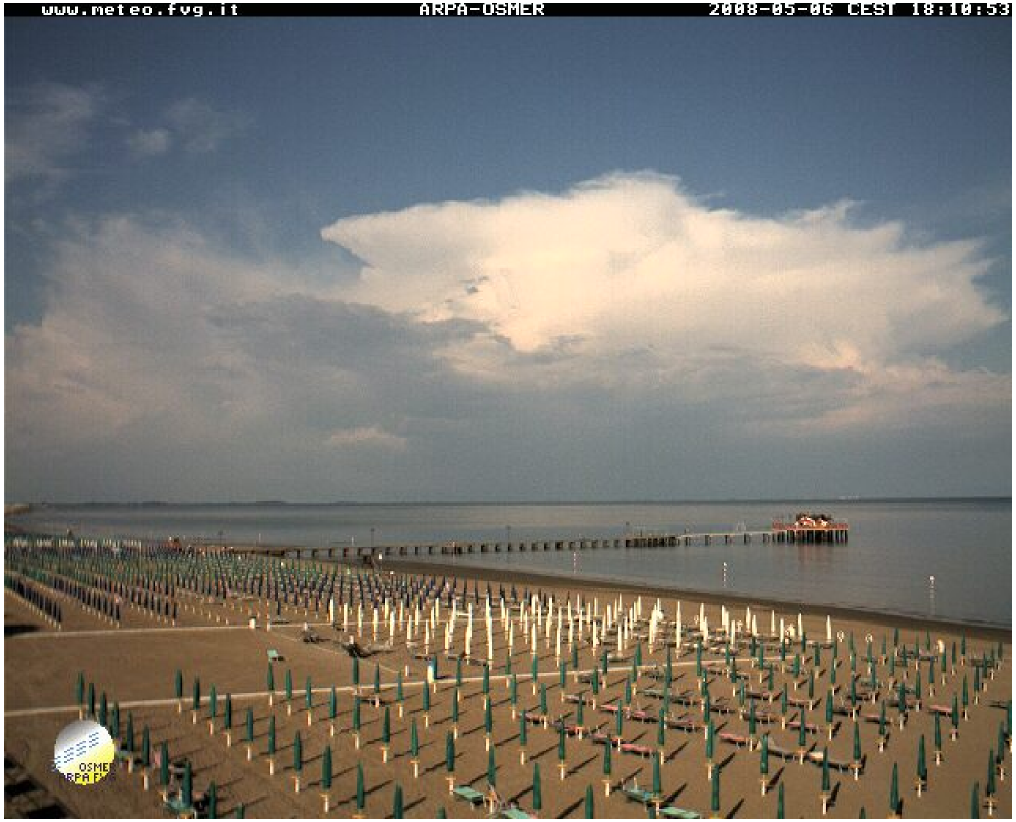
differences





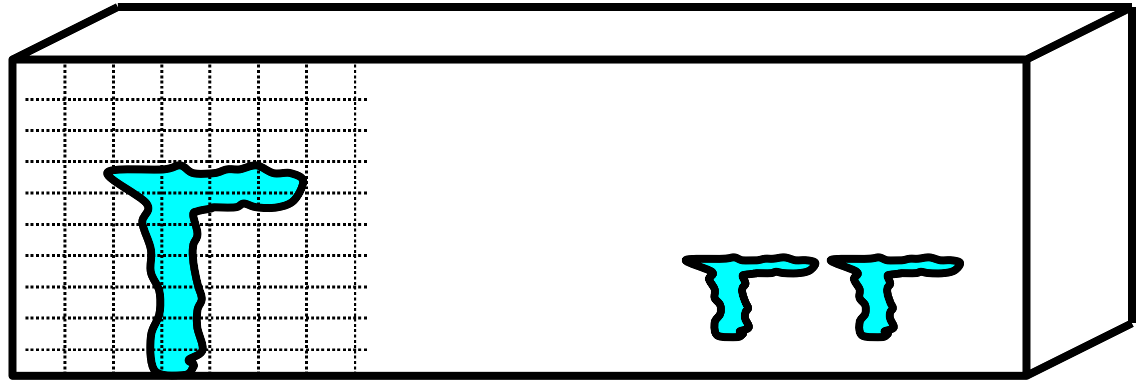


The task of cloud parametrization



The task of cloud parametrization

1. Geometry
2. Microphysics



- Given a fine-enough resolution to resolve the cloud motions, can assume
  - Grid-box entirely filled with cloud condensate
  - Neglect sub-grid variability of condensate
- Parametrization task is then one of representing the microphysics of clouds
- Define a number of bulk categories (small/large ice, graupel, rain etc) and parametrization the rate equations governing the conversion terms

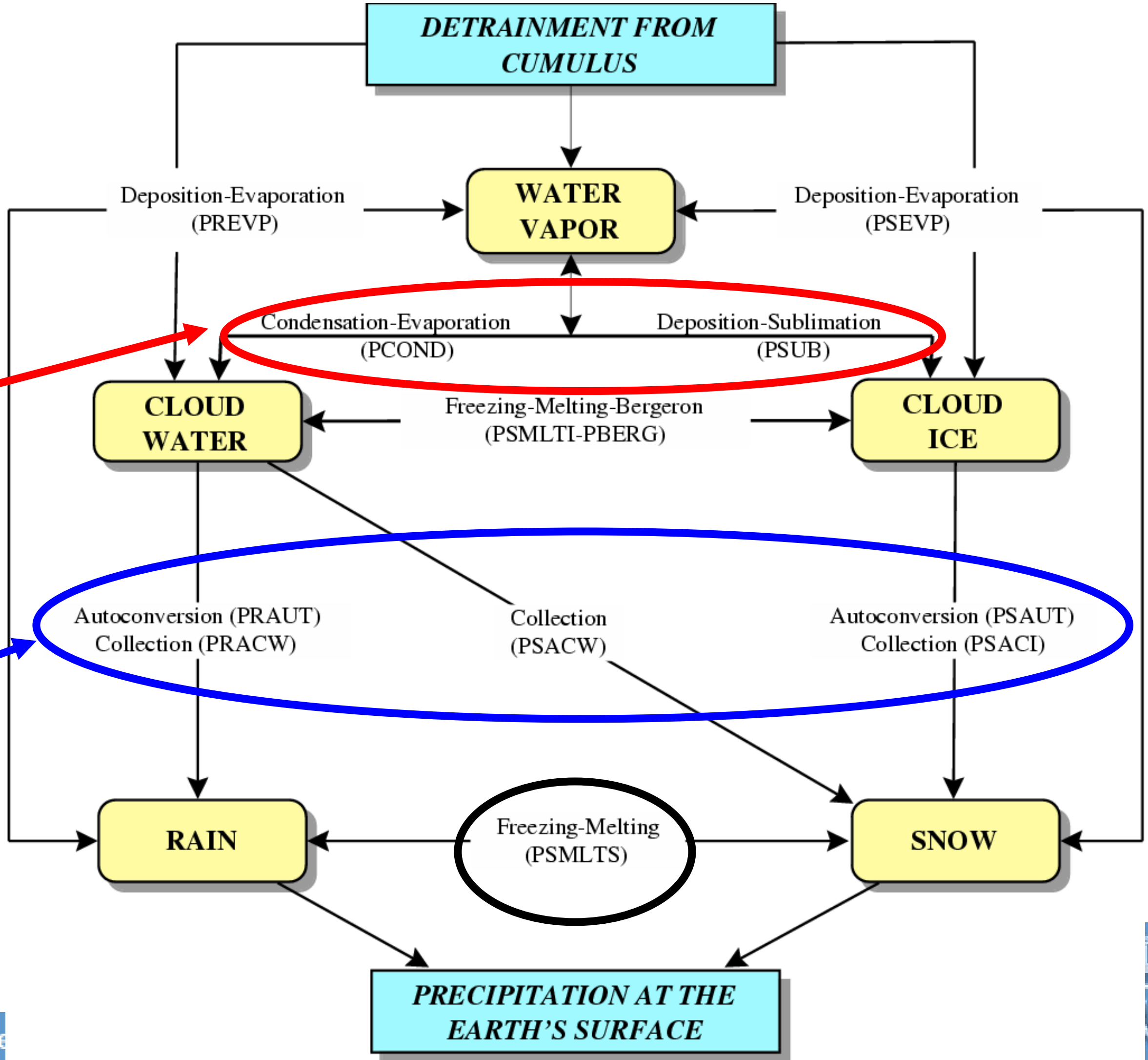
Microphysics - a 5-category GCM scheme

Fowler et al., JCL, 1996

Similar complexity to many schemes in use in CRMs

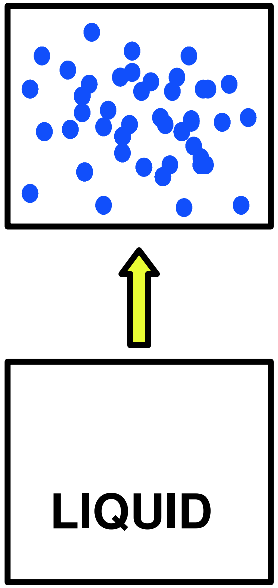
Mostly treated as instant "No supersaturation assumption"

"Threshold" linear or exponential terms with efficiency adjustments



An important distinction liquid/ice

- Warm clouds
  - Condensation occurs at RH=100%
  - Condensation and evaporation processes fast
  - Cloud droplet fall-speeds small, consider in suspension
- Can consider total water variable qt=qv+ql



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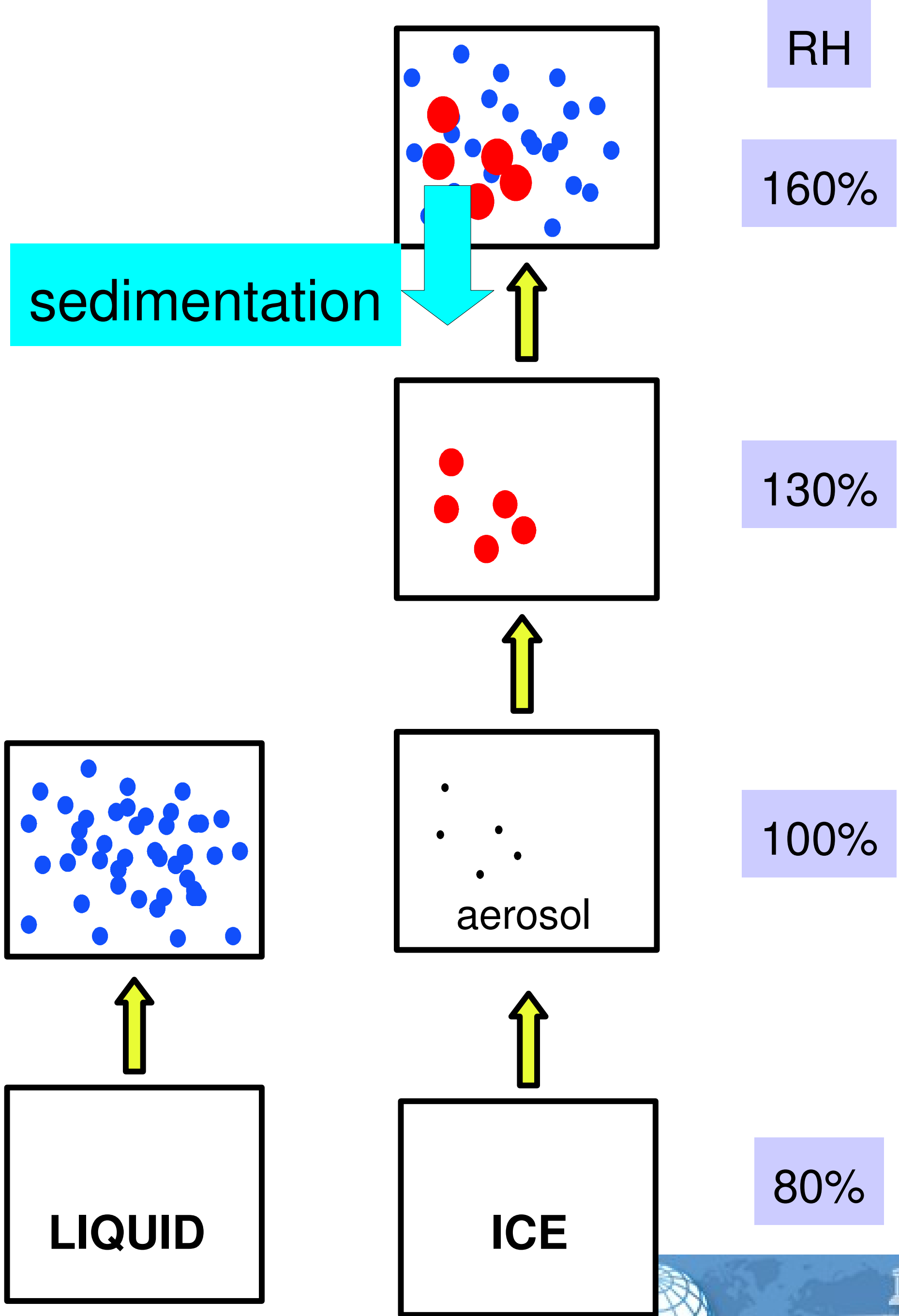
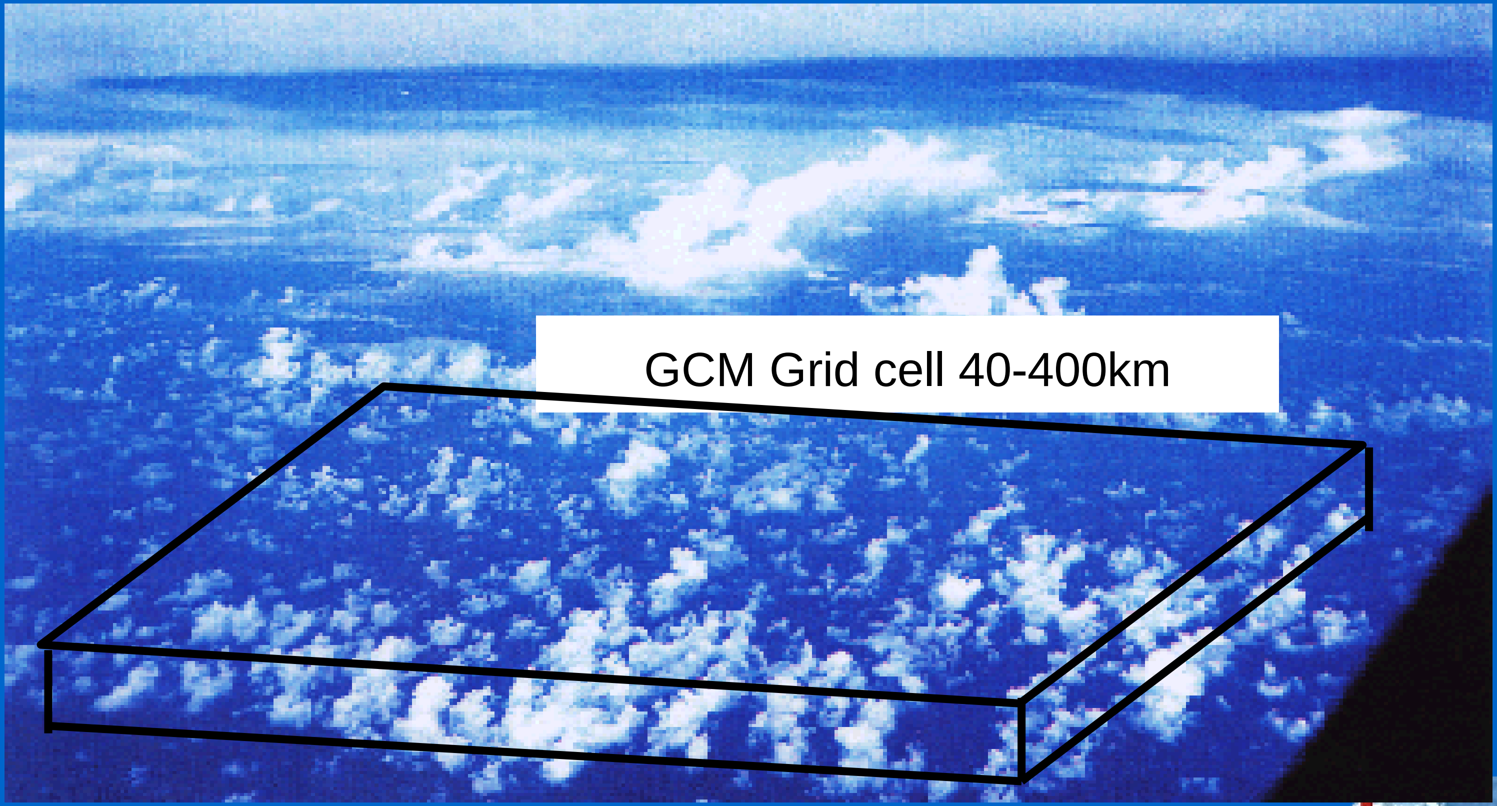


Clouds in GCMs – the geometrical issues

Clouds are subgrid-scale

(both horizontally and vertically)



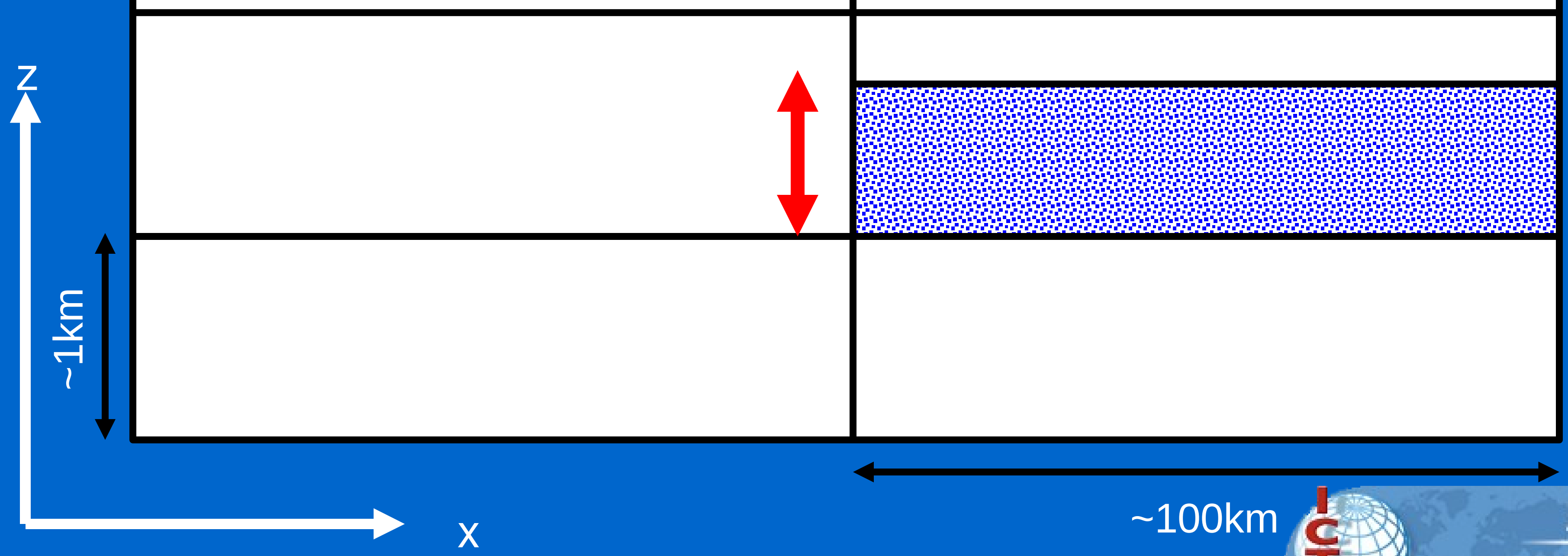
How can we describe clouds? Which characteristics?

VERTICAL COVERAGE

Most models assume that this is 1

This can be a poor assumption with coarse vertical grids.

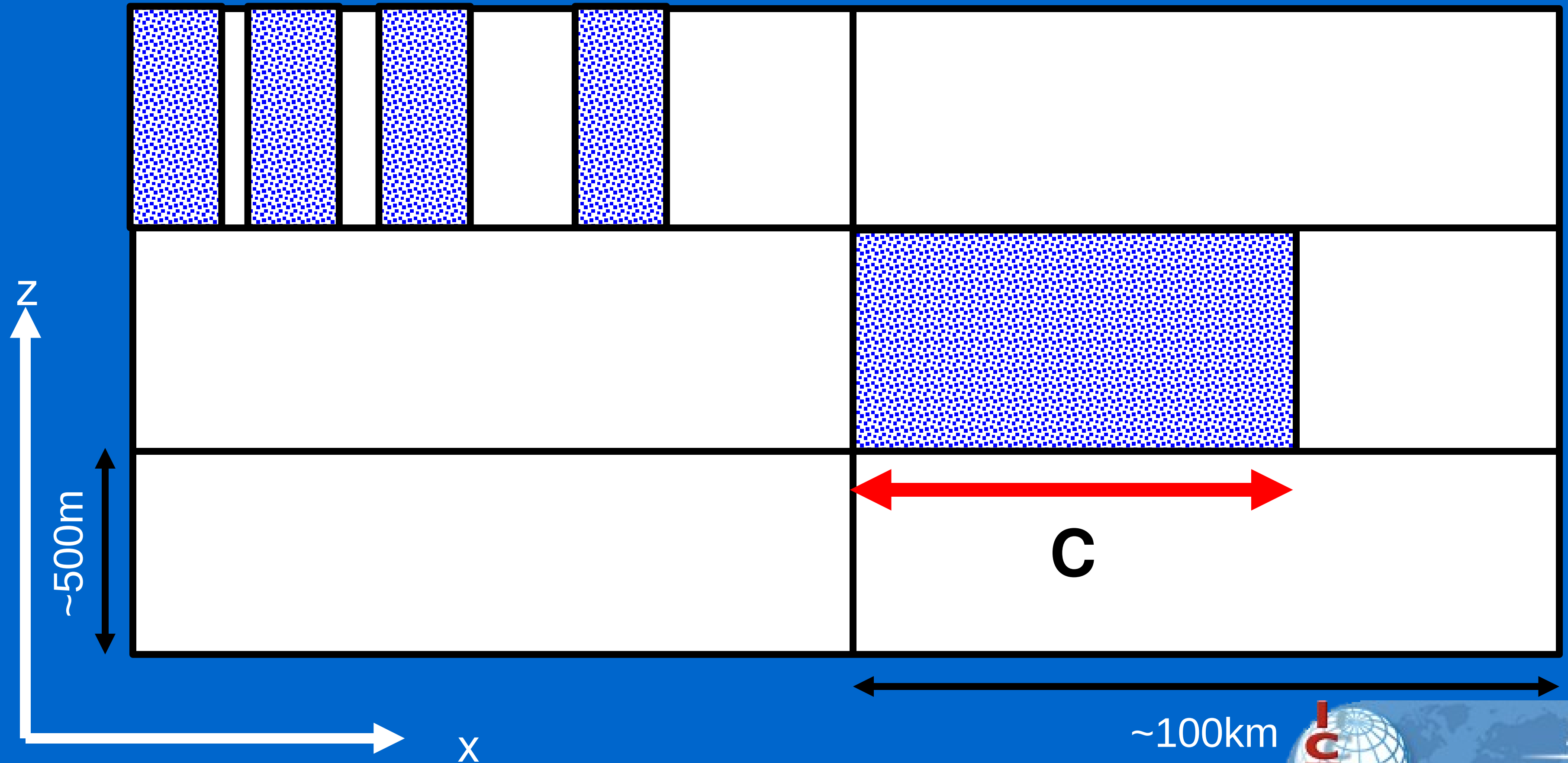
Many climate models still use fewer than 30 vertical levels currently, some recent examples still use only 9 levels



How can we describe clouds? Which characteristics?

HORIZONTAL COVERAGE, C

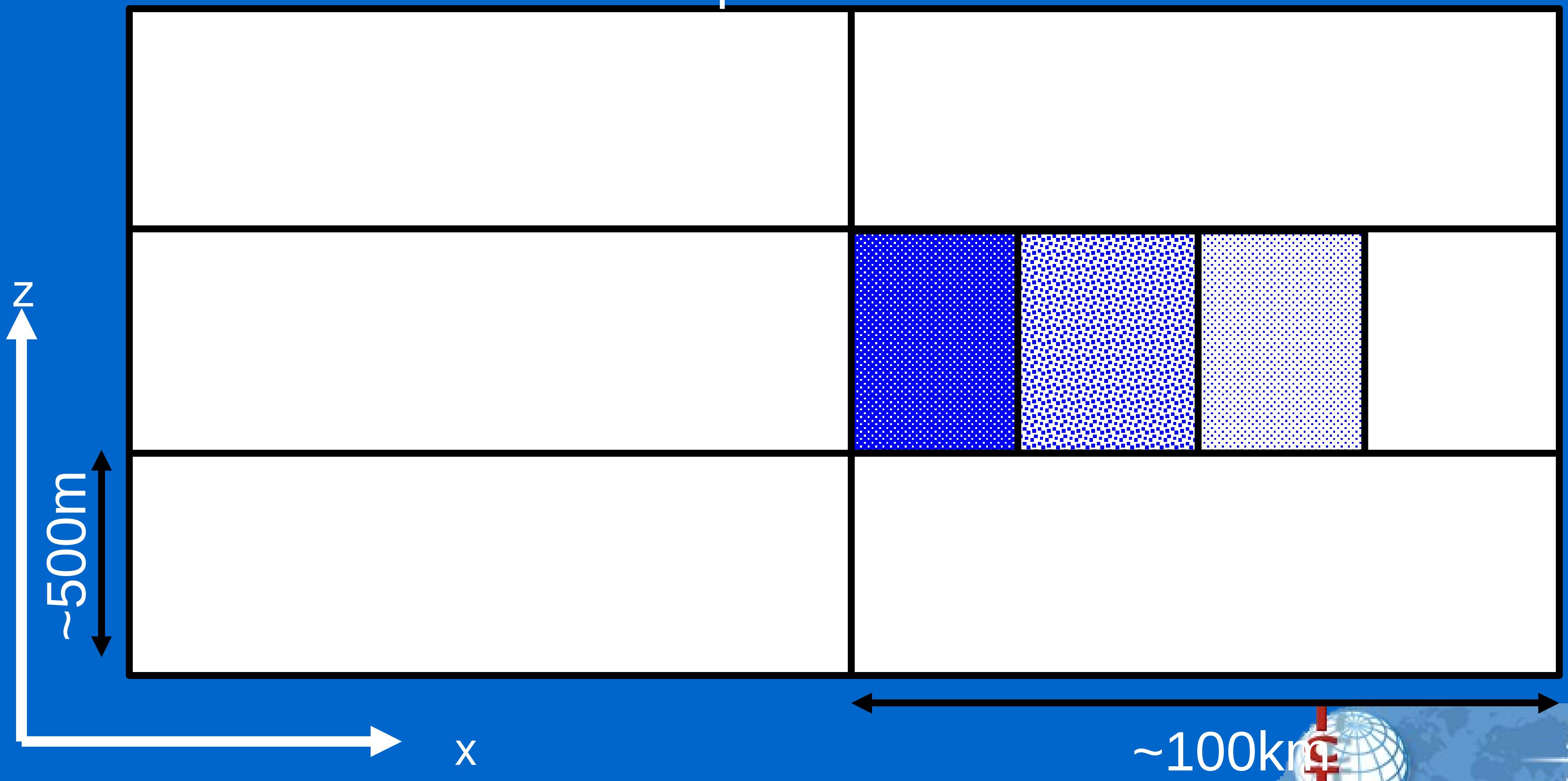
Spatial arrangement?



How can we describe clouds? Which characteristics?

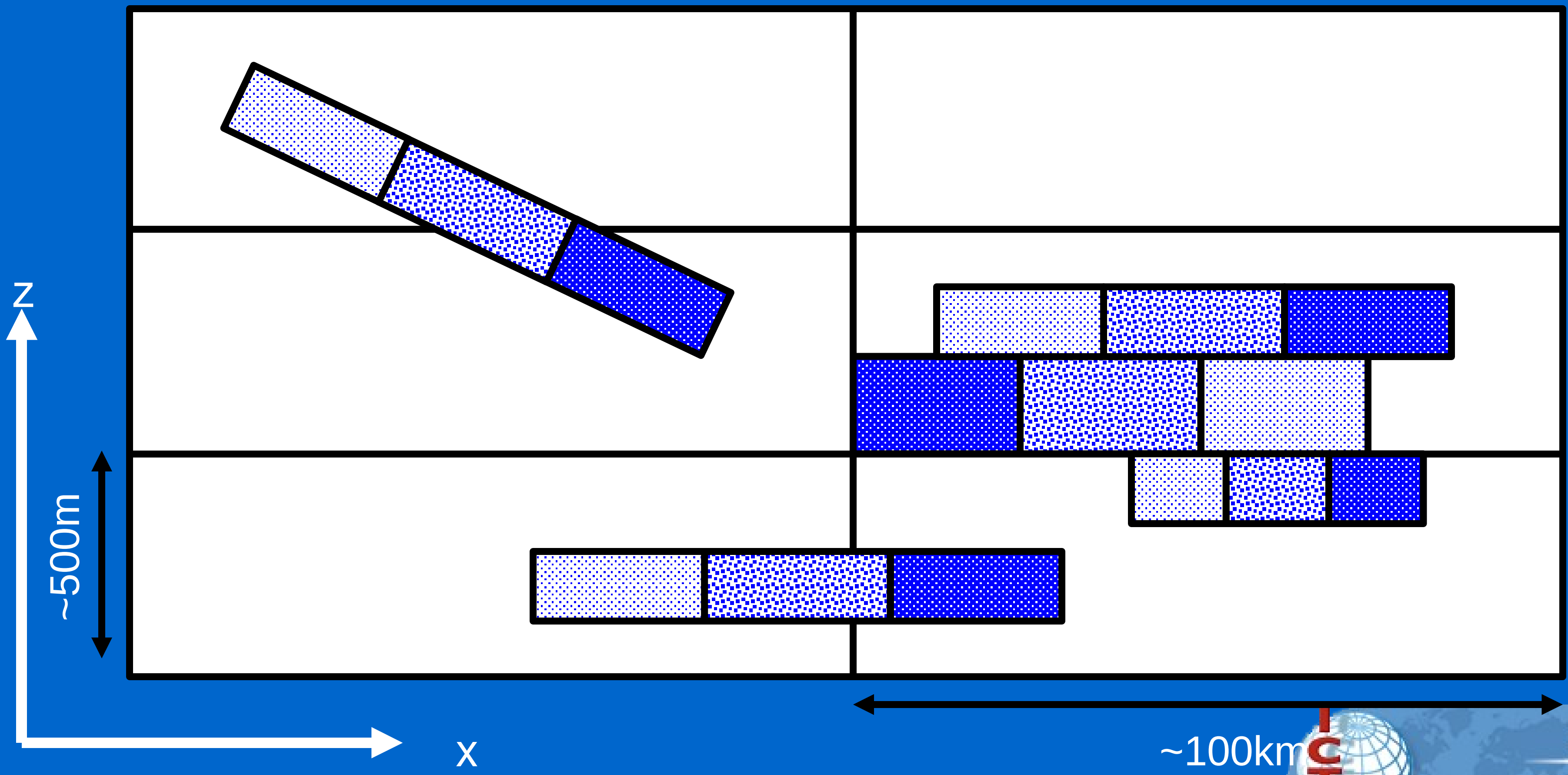
IN-CLOUD INHOMOGENEITY

in terms of cloud particle size and number



Macroscale Issues of Parameterization

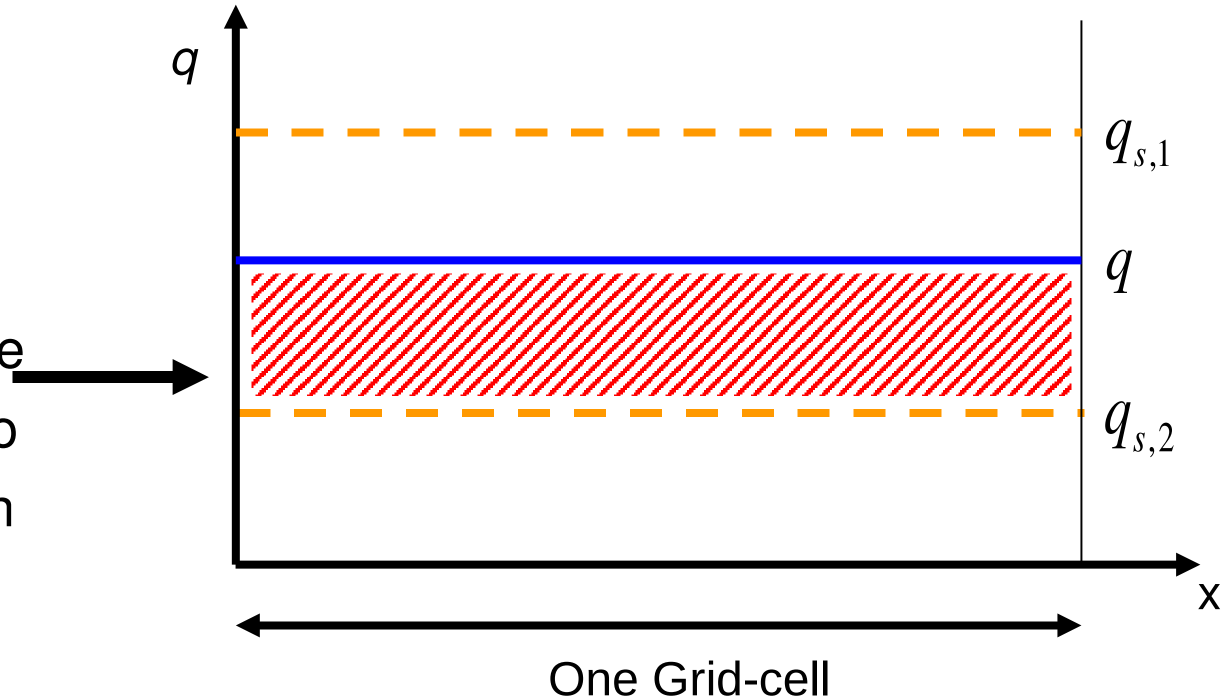
Just these issues can become a little complex!!!



Partial cloud cover

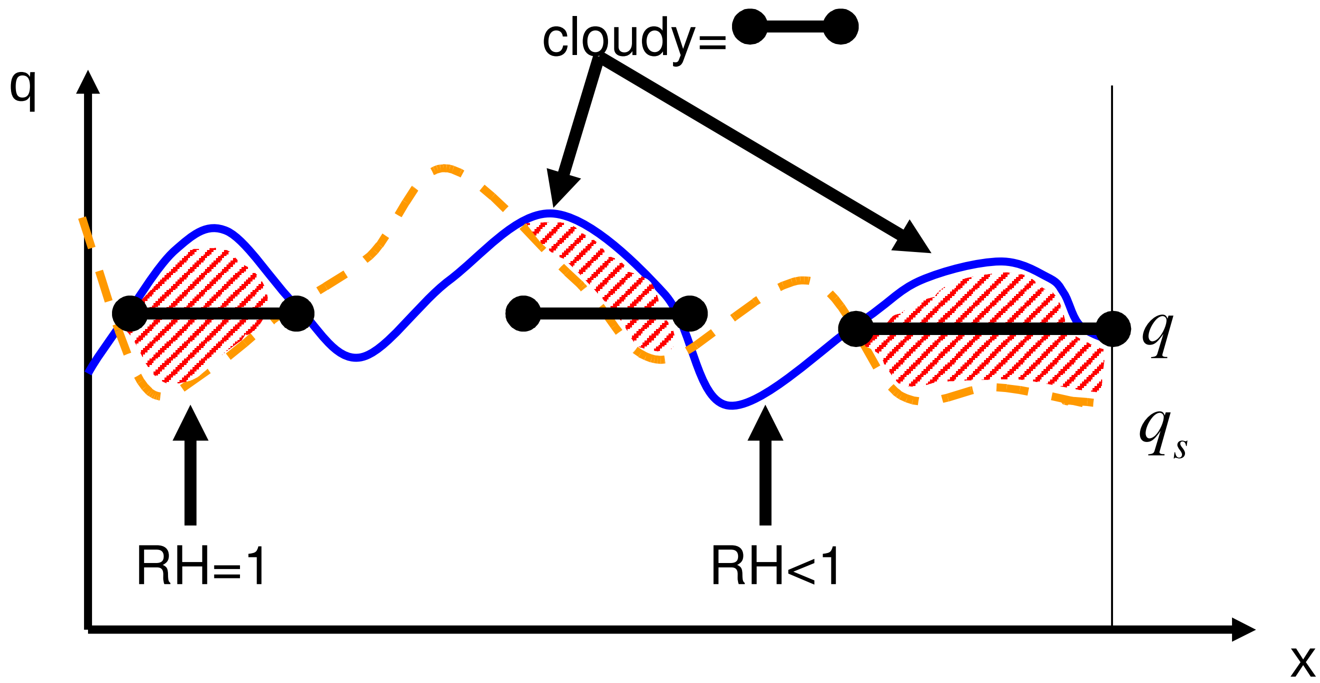
Homogeneous Distribution of water vapour and temperature:

Note in the second case the relative humidity=1 if no supersaturation allowed



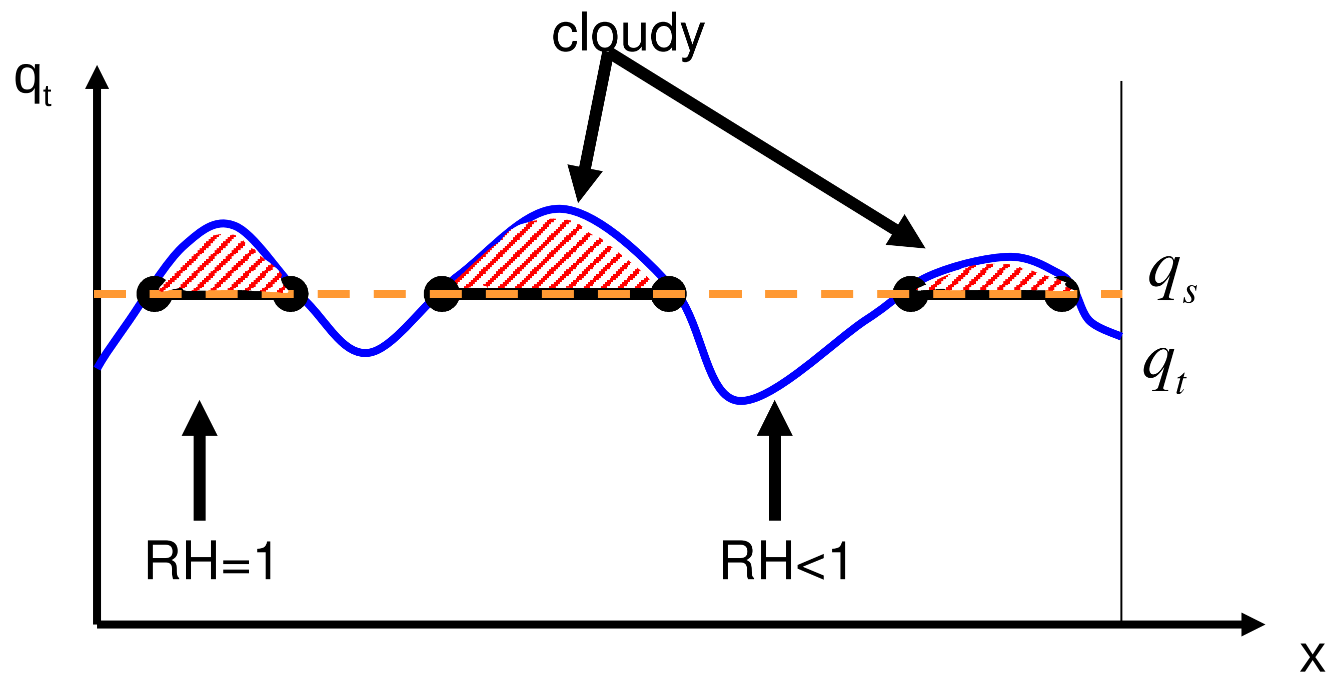
Partial coverage of a grid-box with clouds is only possible if there is a inhomogeneous distribution of temperature and/or humidity.

Heterogeneous distribution of T and q



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

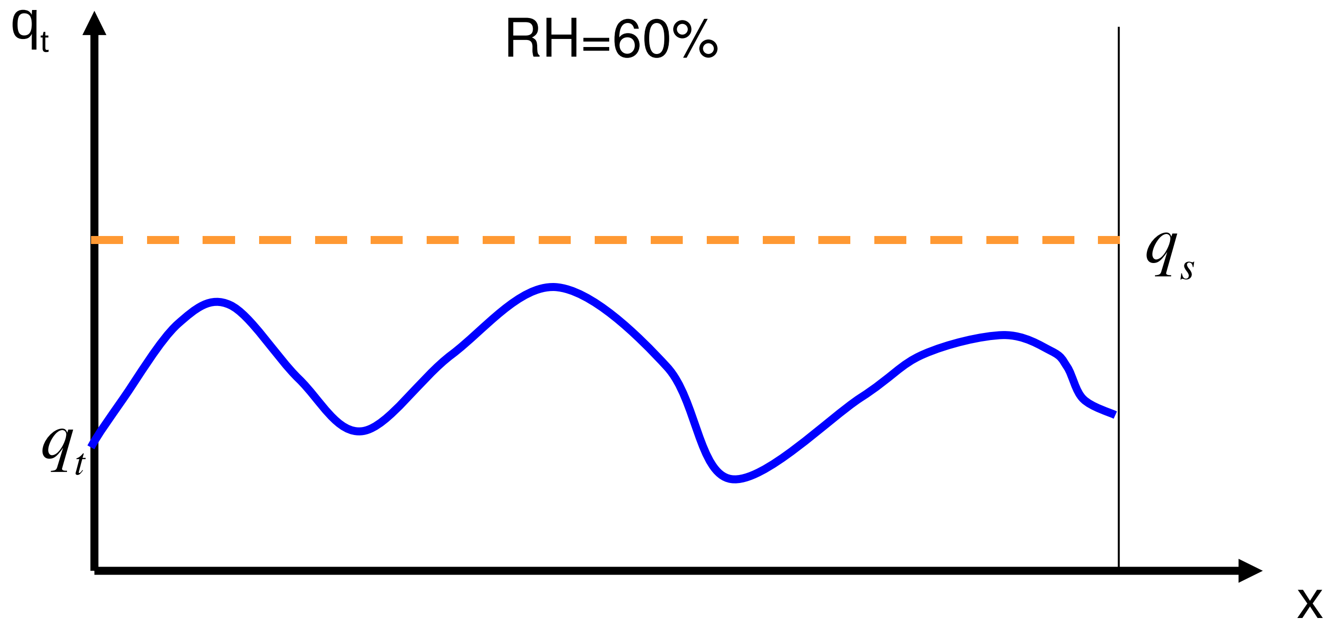
The interpretation does not change much if we only consider humidity variability



Throughout this talk I will neglect temperature variability

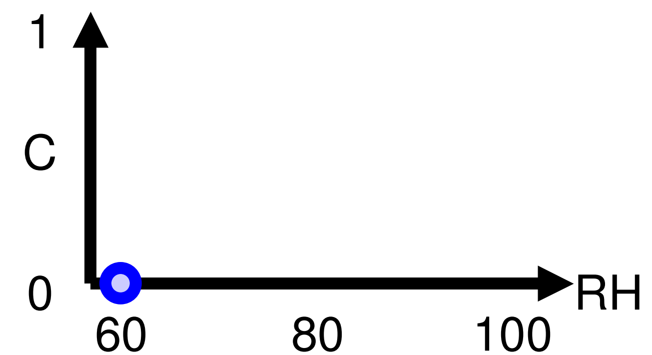
In fact : Analysis of observations and model data indicates humidity fluctuations are more important

Simple diagnostic schemes: RH-based schemes

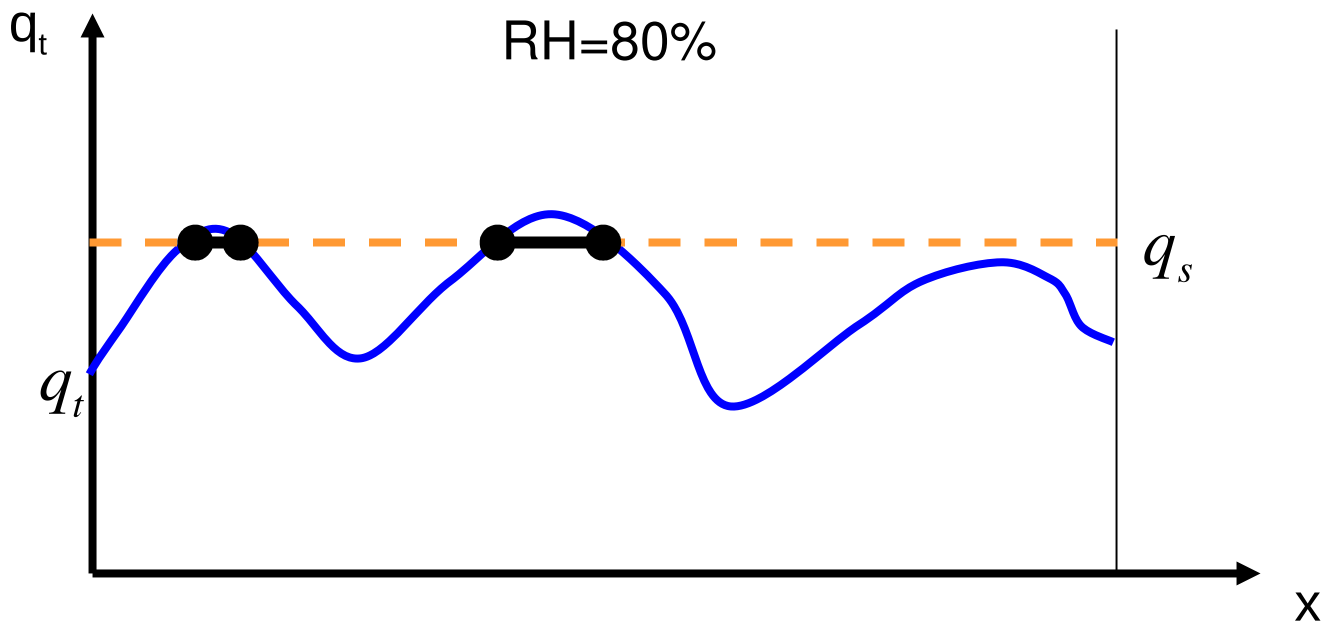


Take a grid cell with a certain (fixed) distribution of total water.

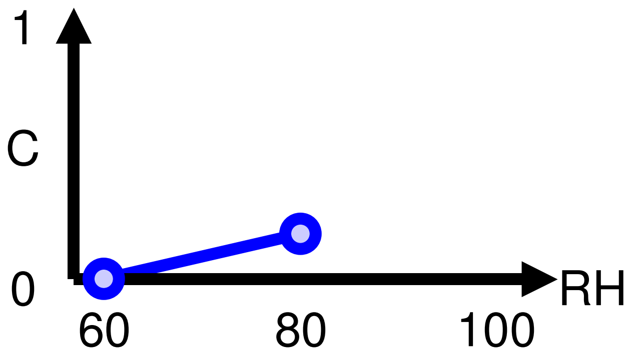
At low mean RH, the cloud cover is zero, since even the moistest part of the grid cell is subsaturated



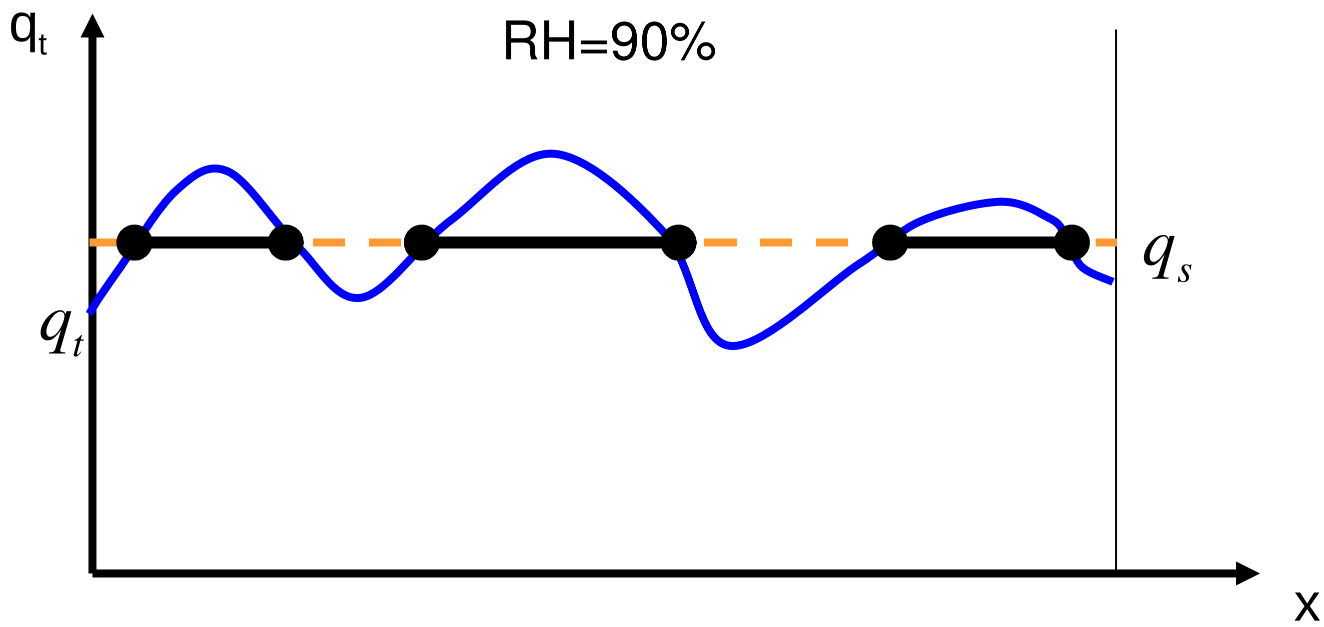
Simple diagnostic schemes: RH-based schemes



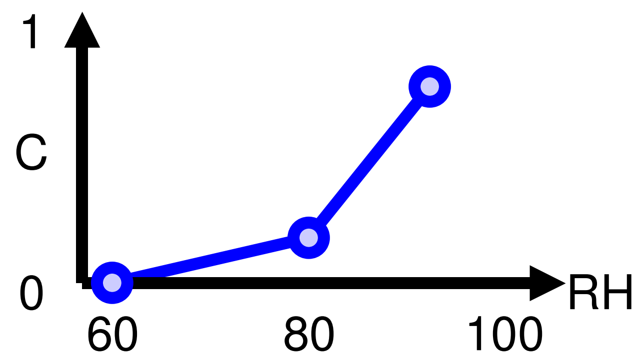
Add water vapour to the gridcell, the moistest part of the cell become saturated and cloud forms. The cloud cover is low.



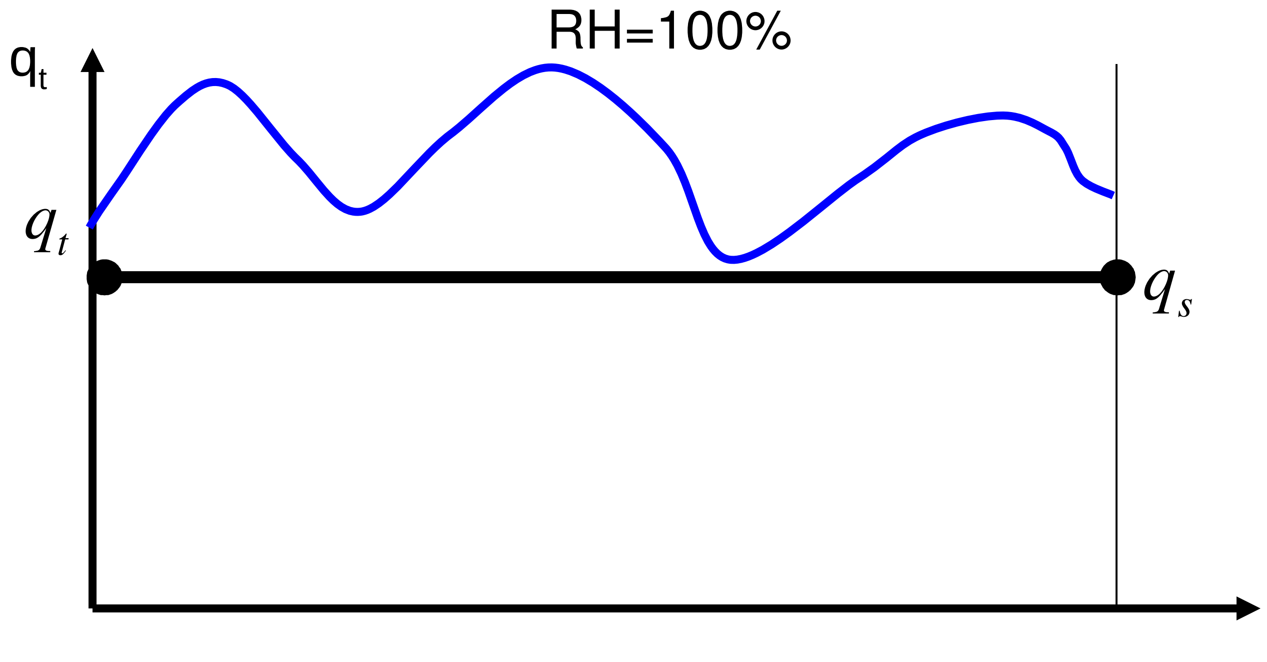
Simple diagnostic schemes: RH-based schemes



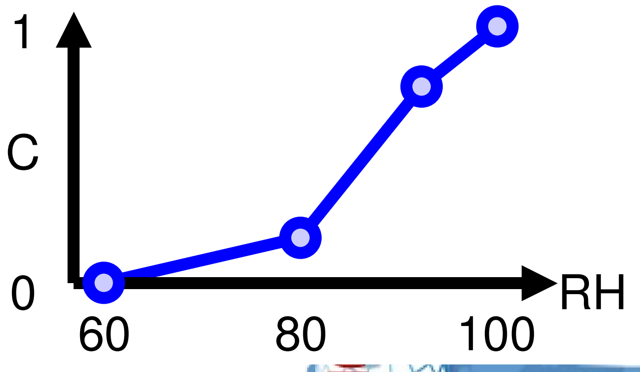
Further increases in RH increase the cloud cover



Simple diagnostic schemes: RH-based schemes



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



Diagnostic Relative Humidity Schemes

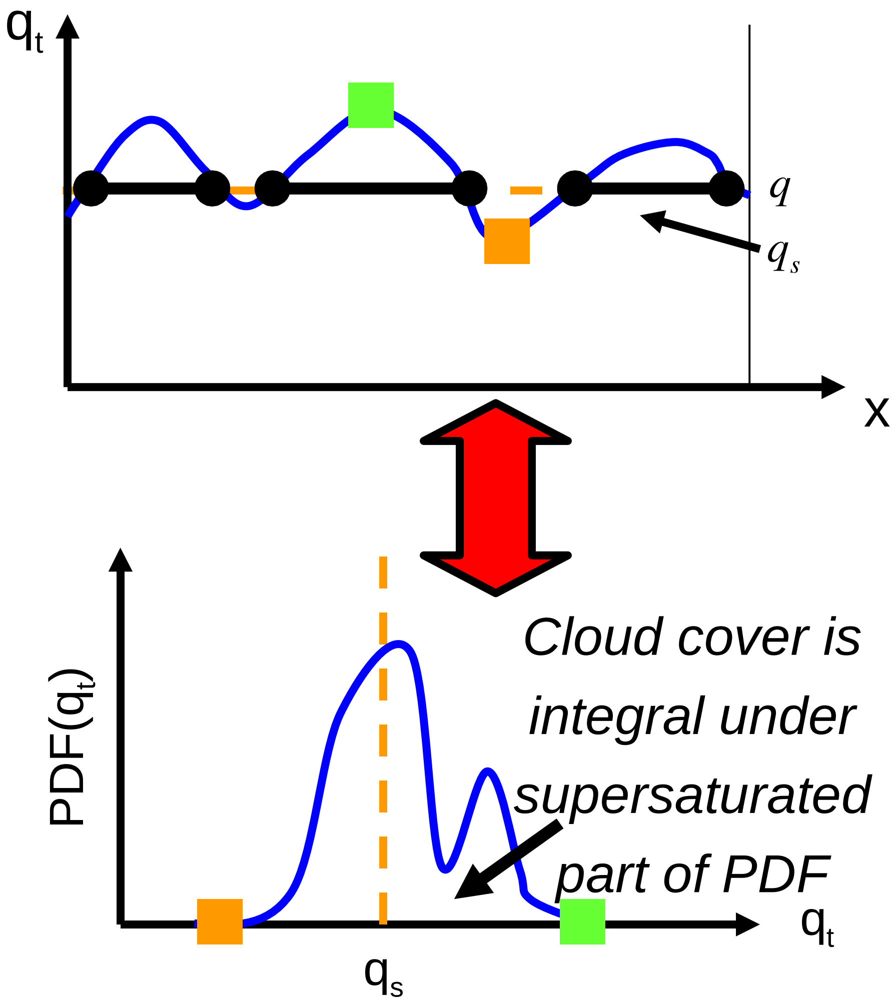
- Cloud cover not well coupled to other processes
- In reality, different cloud types with different coverage can exist with same relative humidity. This can not be represented

Statistical Schemes

- These explicitly specify the probability density function (PDF) for the total water q_t (*and sometimes also temperature*)

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

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



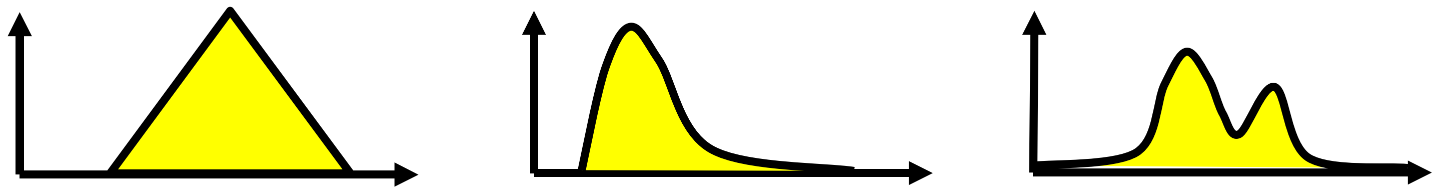
Statistical schemes

- Two tasks: Specification of the:

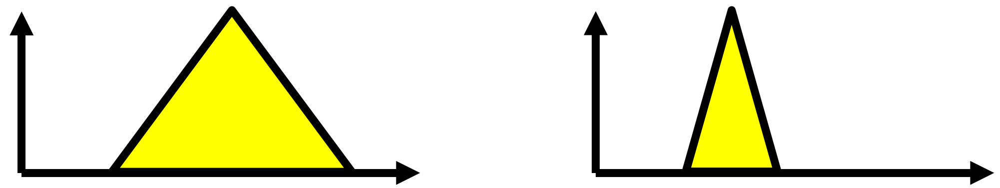
  (1) **PDF shape**

  (2) **PDF moments**

- Shape: Unimodal? bimodal? How many parameters?



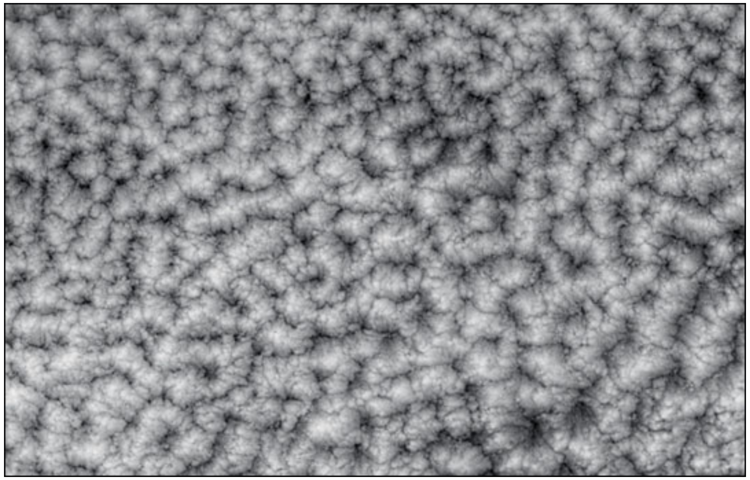
- Moments: How do we set those parameters?



TASK 1: Specification of the PDF

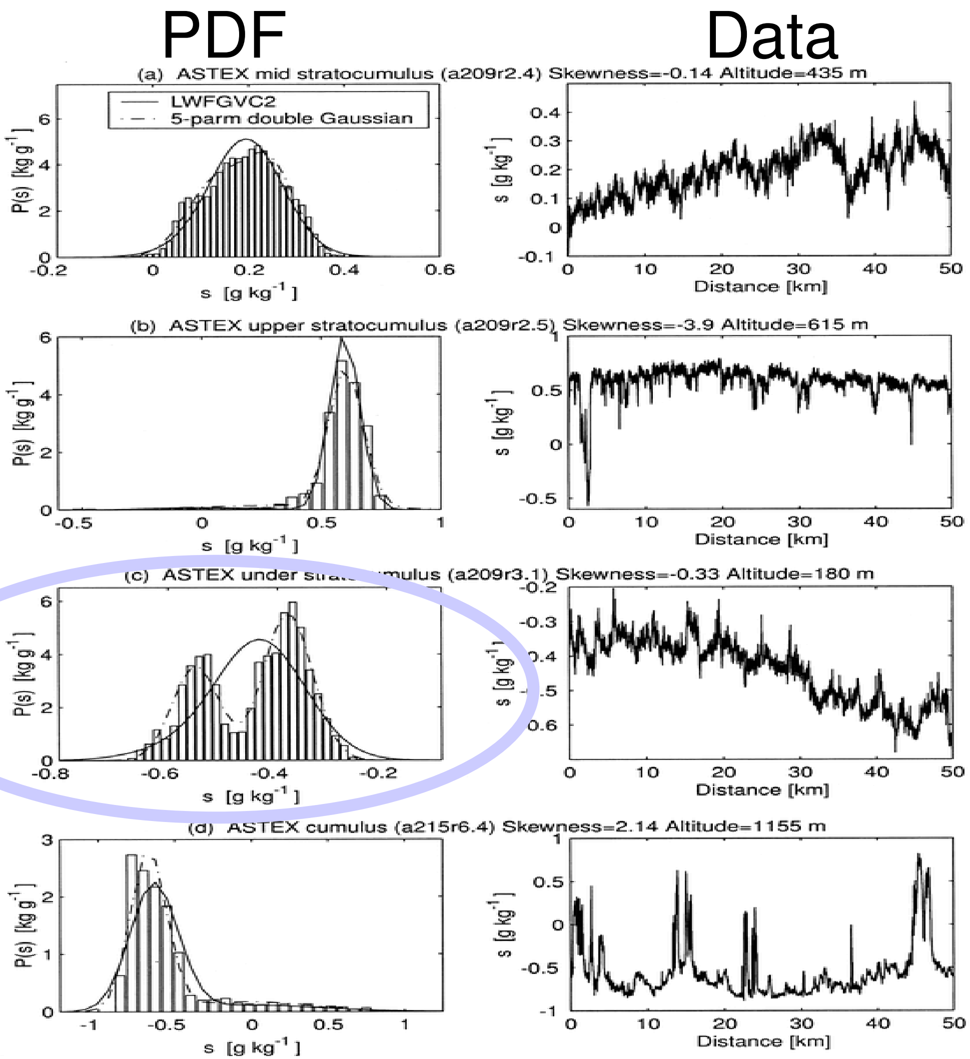
- Lack of observations to determine q_t PDF
  - Aircraft data
    - limited coverage
  - Tethered balloon
    - boundary layer
  - Satellite
    - difficulties resolving in vertical
    - no q_t observations
    - poor horizontal resolution
  - Raman Lidar
    - only PDF of water vapour
- Cloud Resolving models have also been used
    - realism of microphysical parameterisation?

modis image from NASA website



Aircraft data from Larson et al. JAS 01/02

Note significant error that can occur if PDF is unimodal

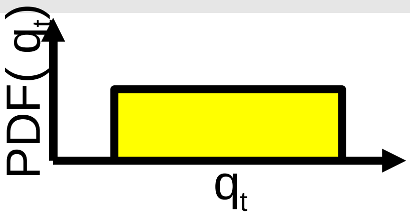


Conclusion: PDFs are mostly approximated by uni or bi-modal distributions, describable by a few parameters

TASK 1: Specification of PDF

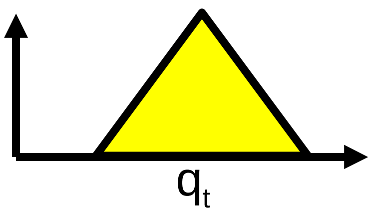
Many function forms have been used

symmetrical distributions:



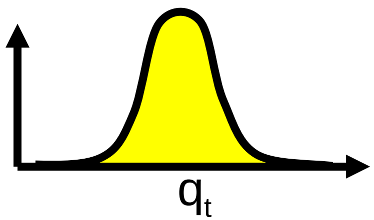
Uniform:

Letreut and Li (91)



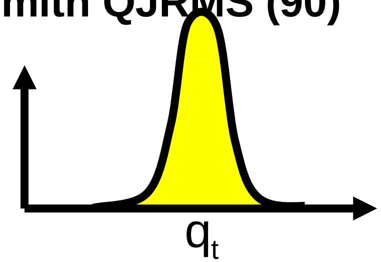
Triangular:

Smith QJRMS (90)



Gaussian:

Mellor JAS (77)



s^4 polynomial:

Lohmann et al. J. Clim (99)

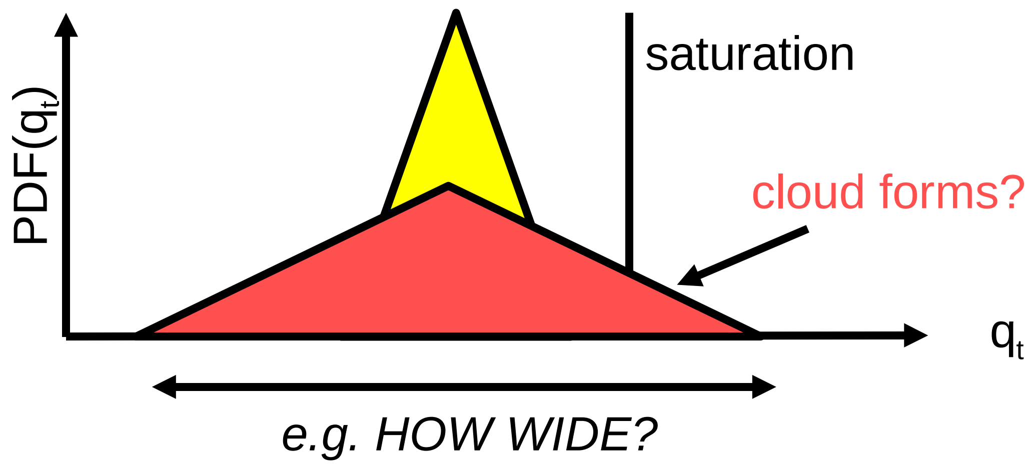
Skewed distributions

- *Exponential*
- *Lognormal*
- *Beta*
- *Gamma*
- *Double Guassian*
- *Double uniform*

TASK 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)

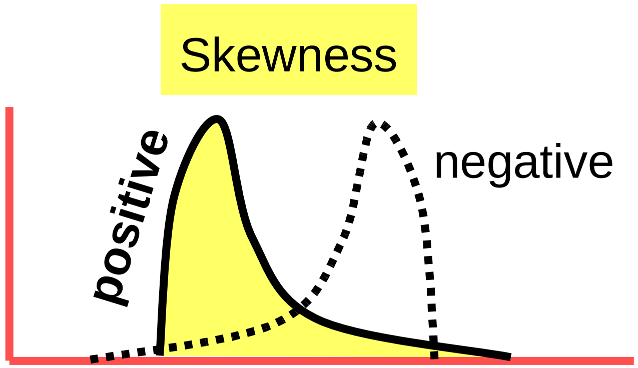


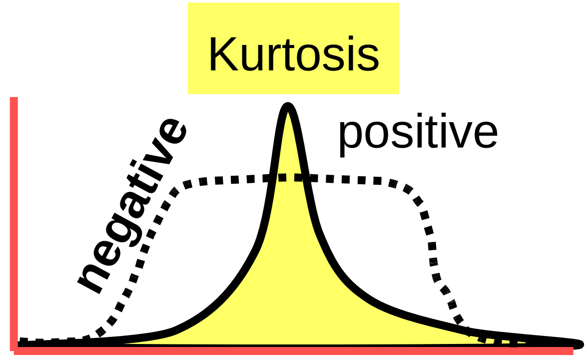
Moment 1=MEAN

Moment 2=VARIANCE

Moment 3=SKEWNESS

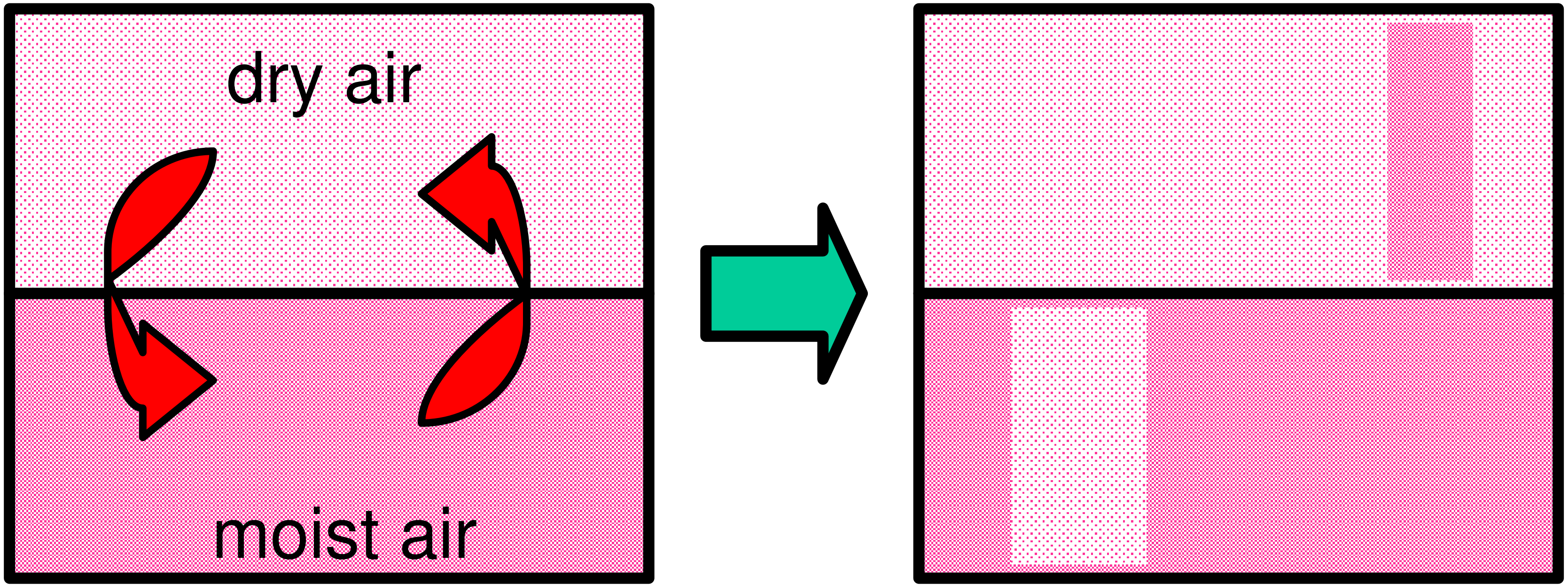
Moment 4=KURTOSIS





Example: Turbulence

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



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

Example: Turbulence

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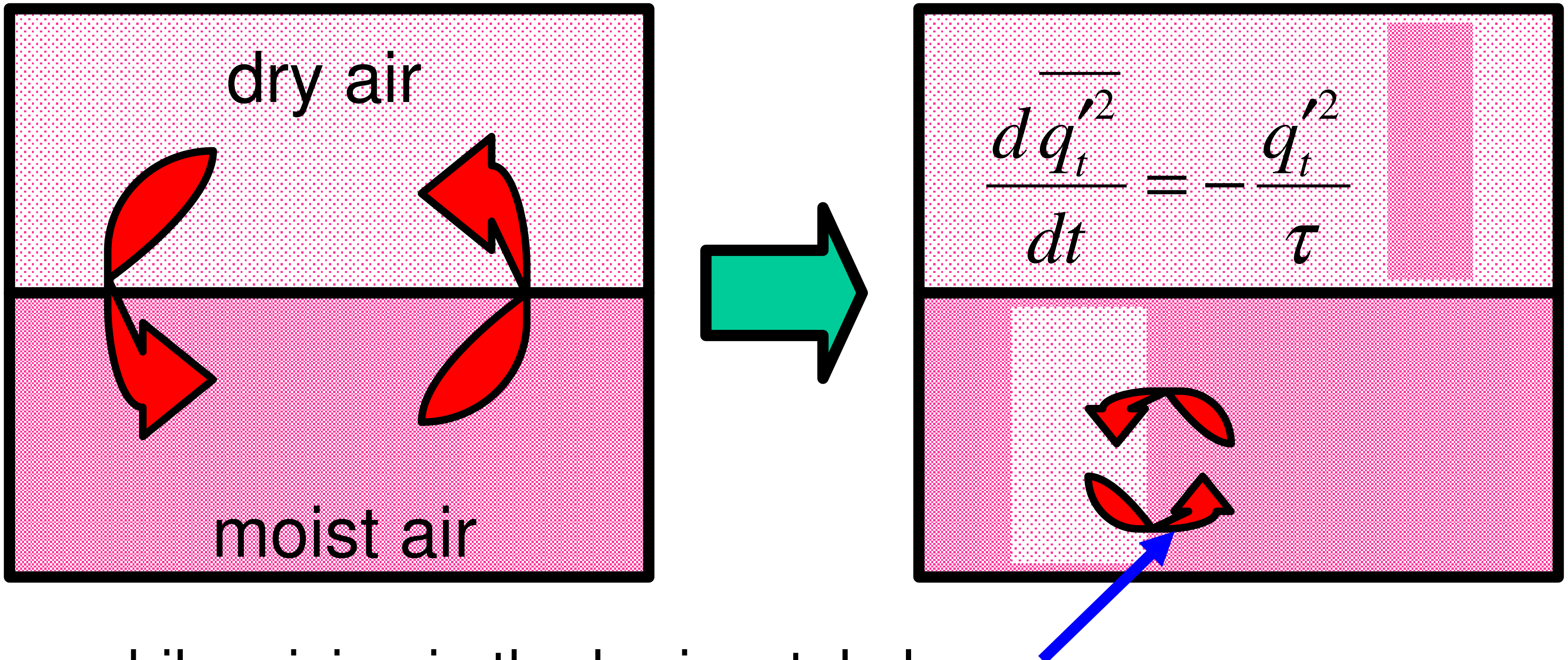
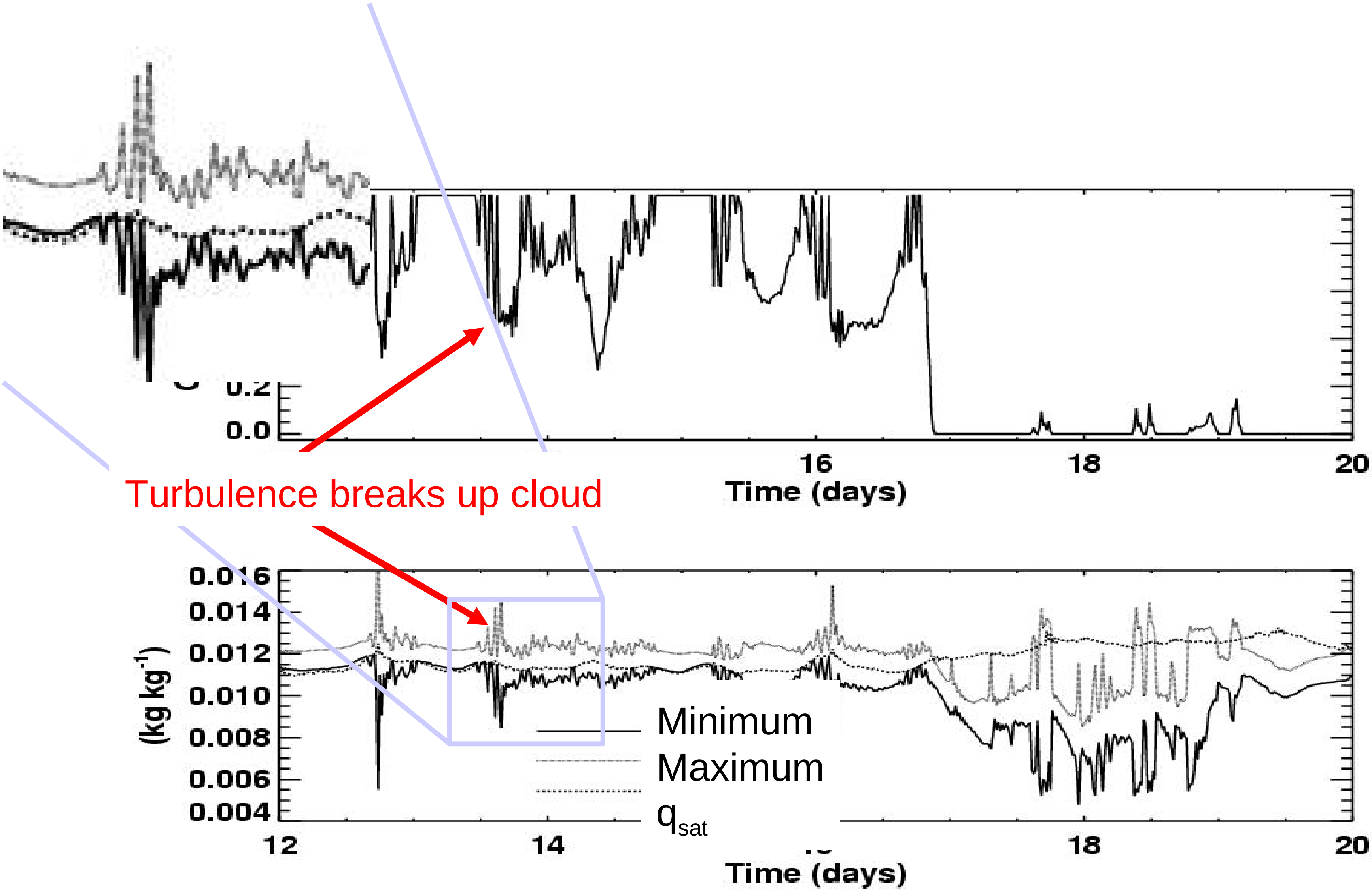
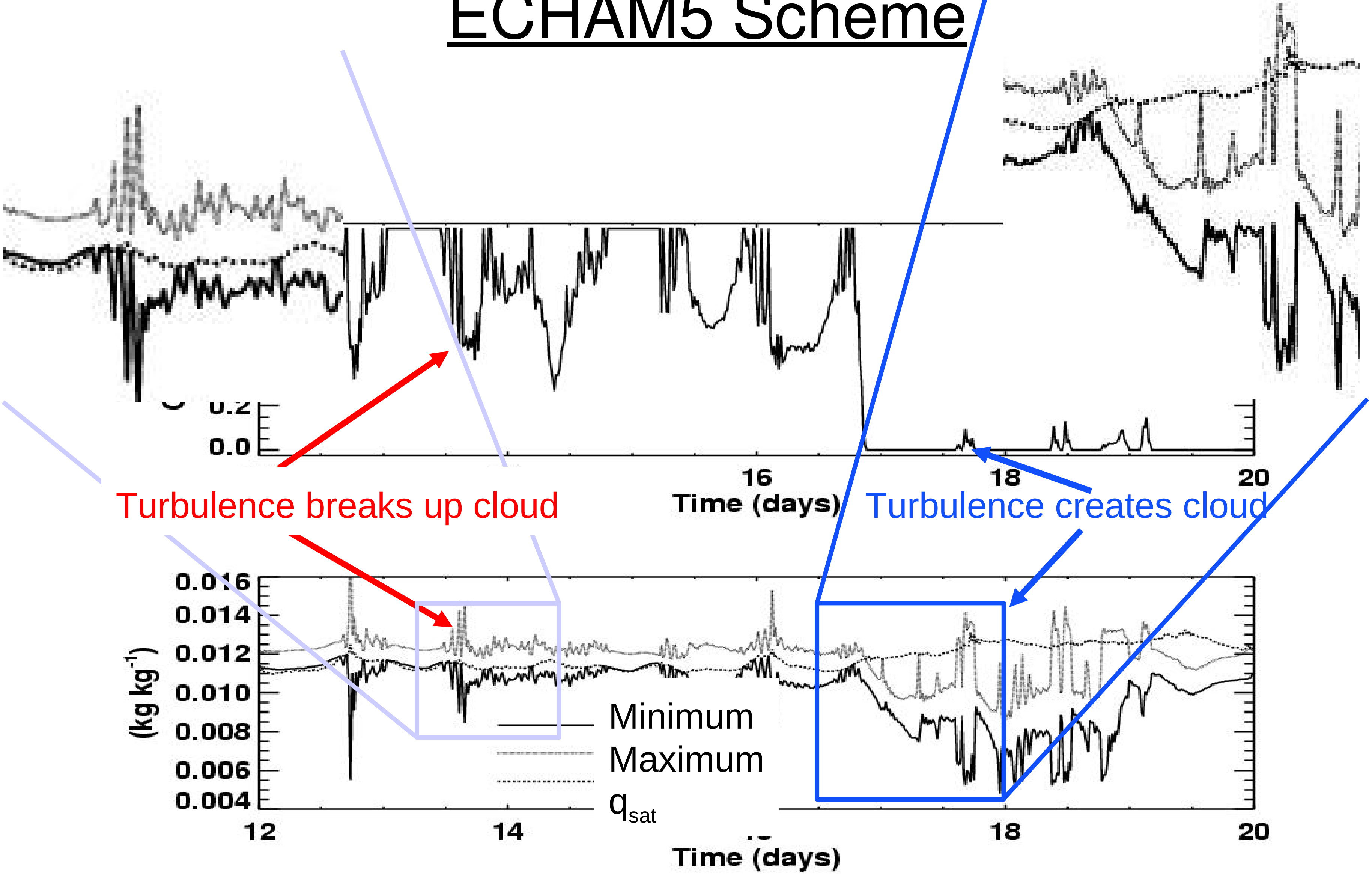


while mixing in the horizontal plane naturally reduces the horizontal variability

ECHAM5 scheme

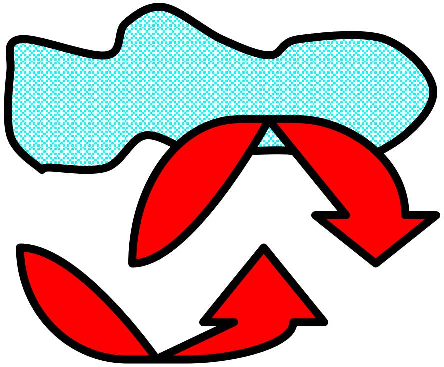


ECHAM5 Scheme



Specification of PDF moments

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



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

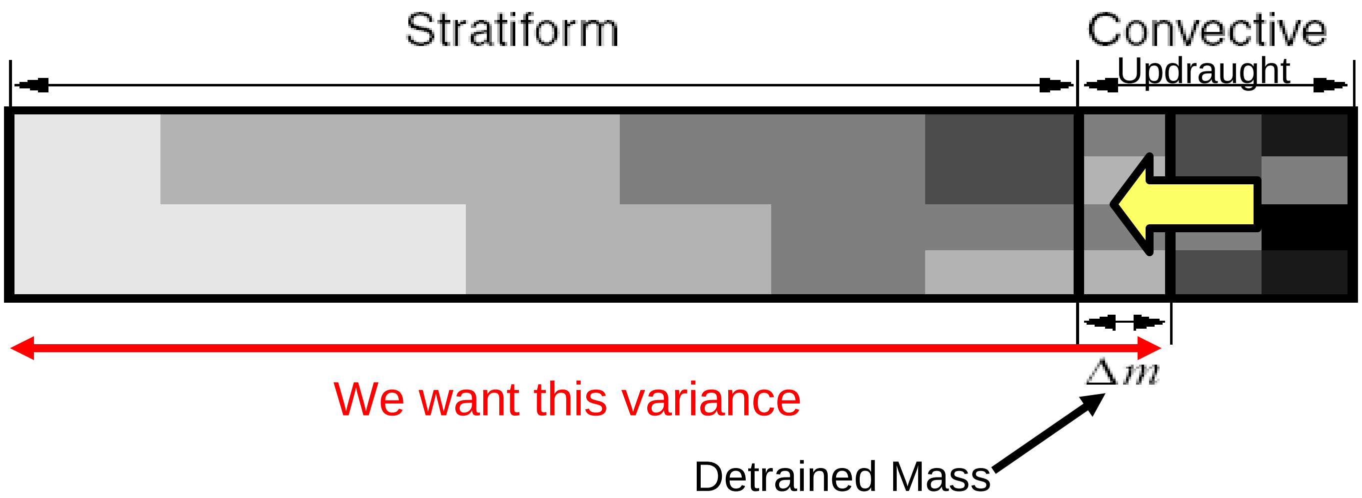
Source dissipation

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*

Convective Detrainment

Klein et al. 2005



closure required for variance in updraught

Klein et al, 2005:

$$D(q_{tu}-q_{te})^2 + D(\sigma^2(q_{tu})-\sigma^2(q_{te})) + \left[gM_c \frac{\partial \sigma^2(q_{te})}{\partial p} \right]$$

D=convective detrainment

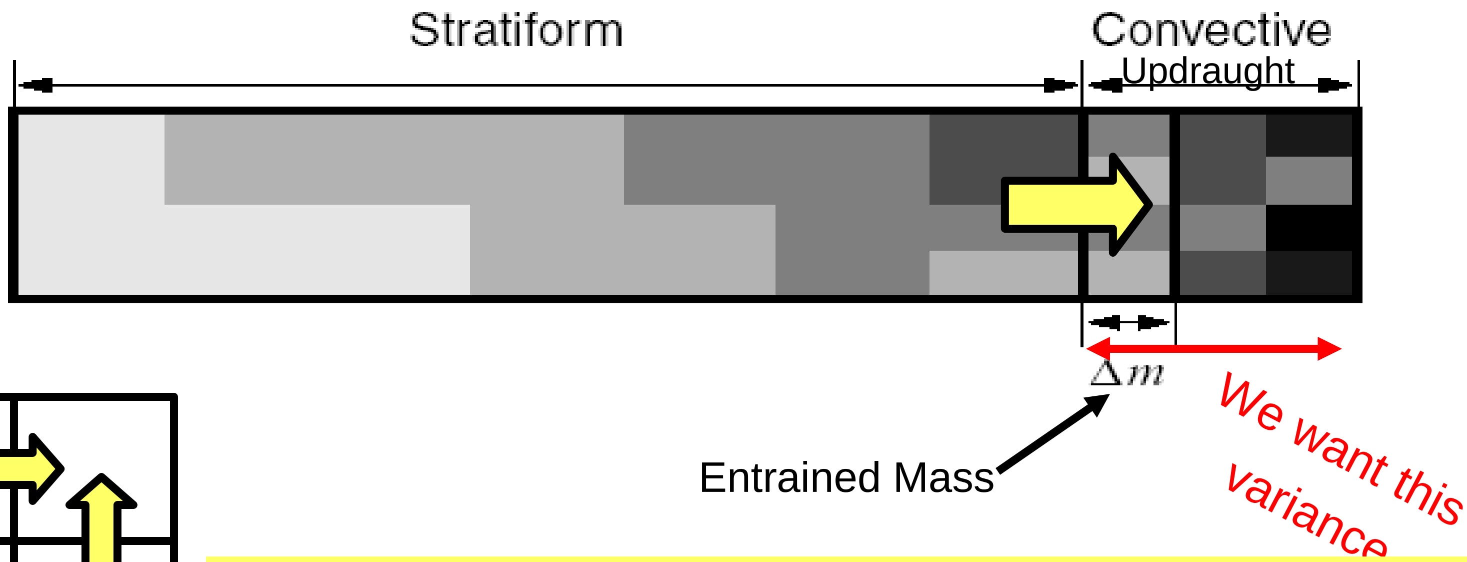
Change due to difference in means

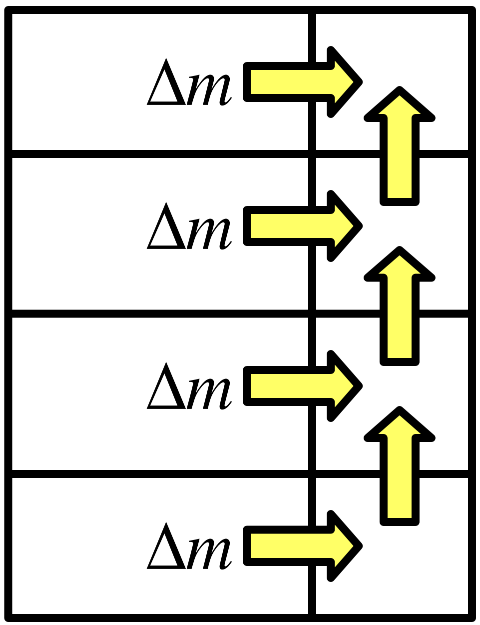
Change due to difference in variance

Transport

Closure for updraft variance: Turn problem on its head

Klein et al. 2005

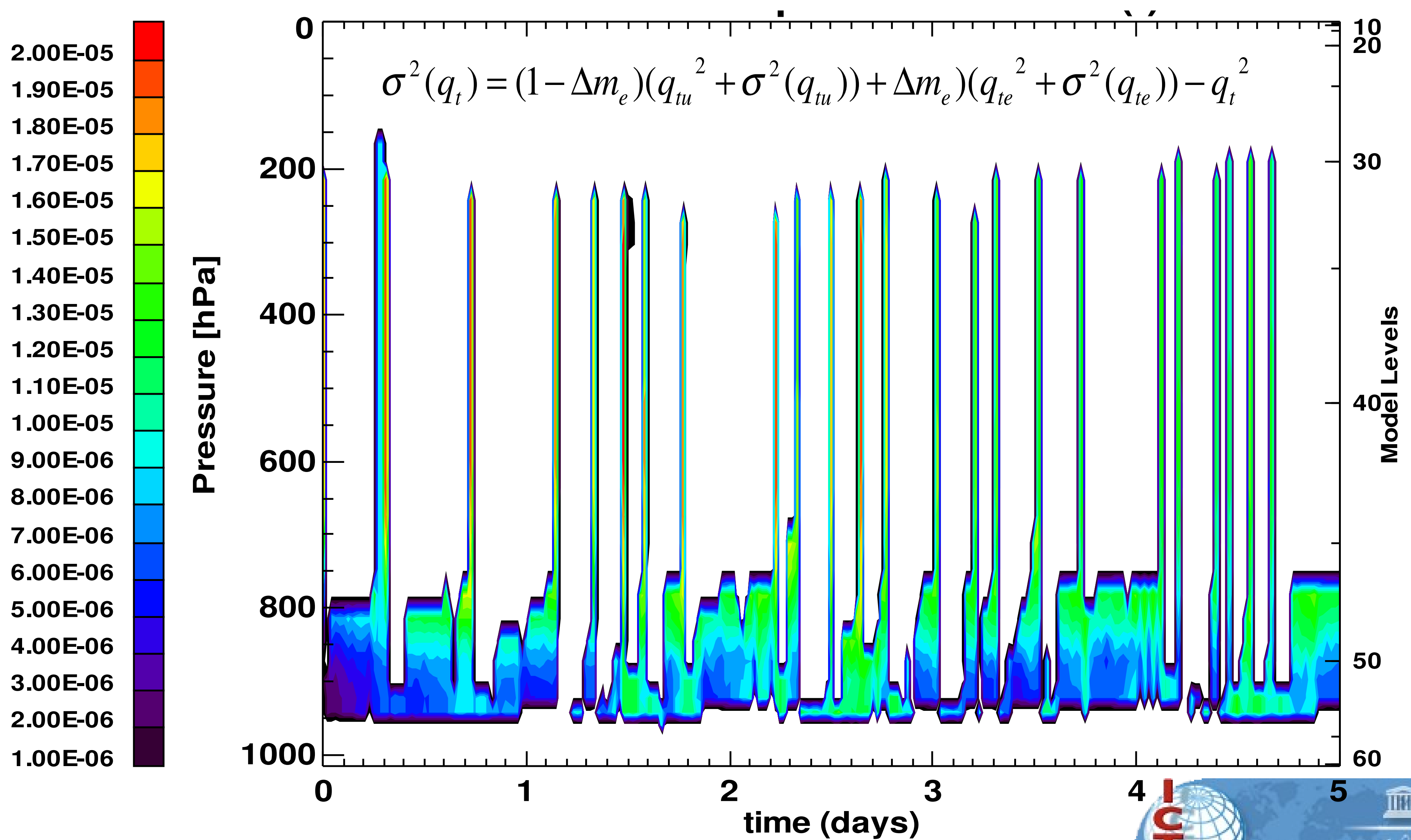




Paradox: This approach increases variance with height in updraught due to entrainment of different fractions, yet other updraught properties (entrainment, velocity etc) are based on a bulk assumption (homogeneous, well mixed, delta function).

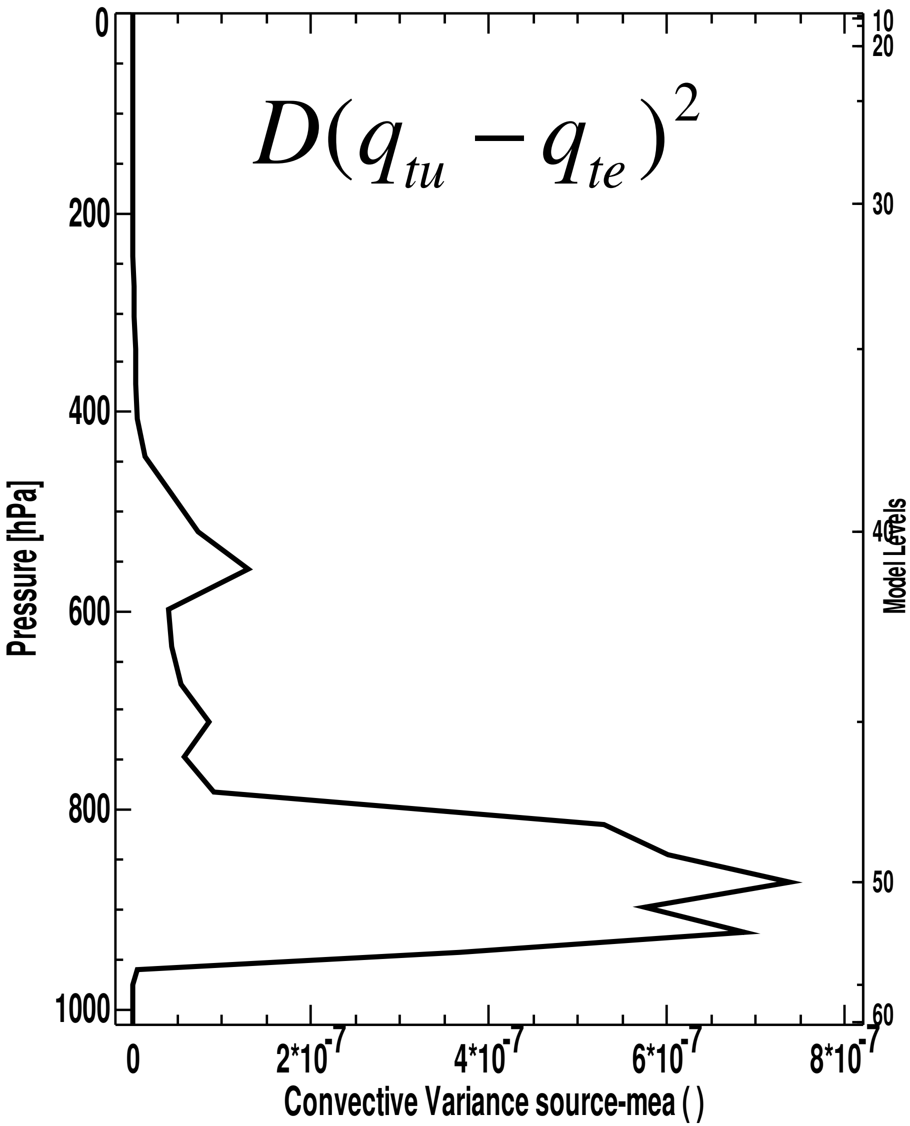
<u>Reality lies between the two extremes due to turbulence and microphysics</u>

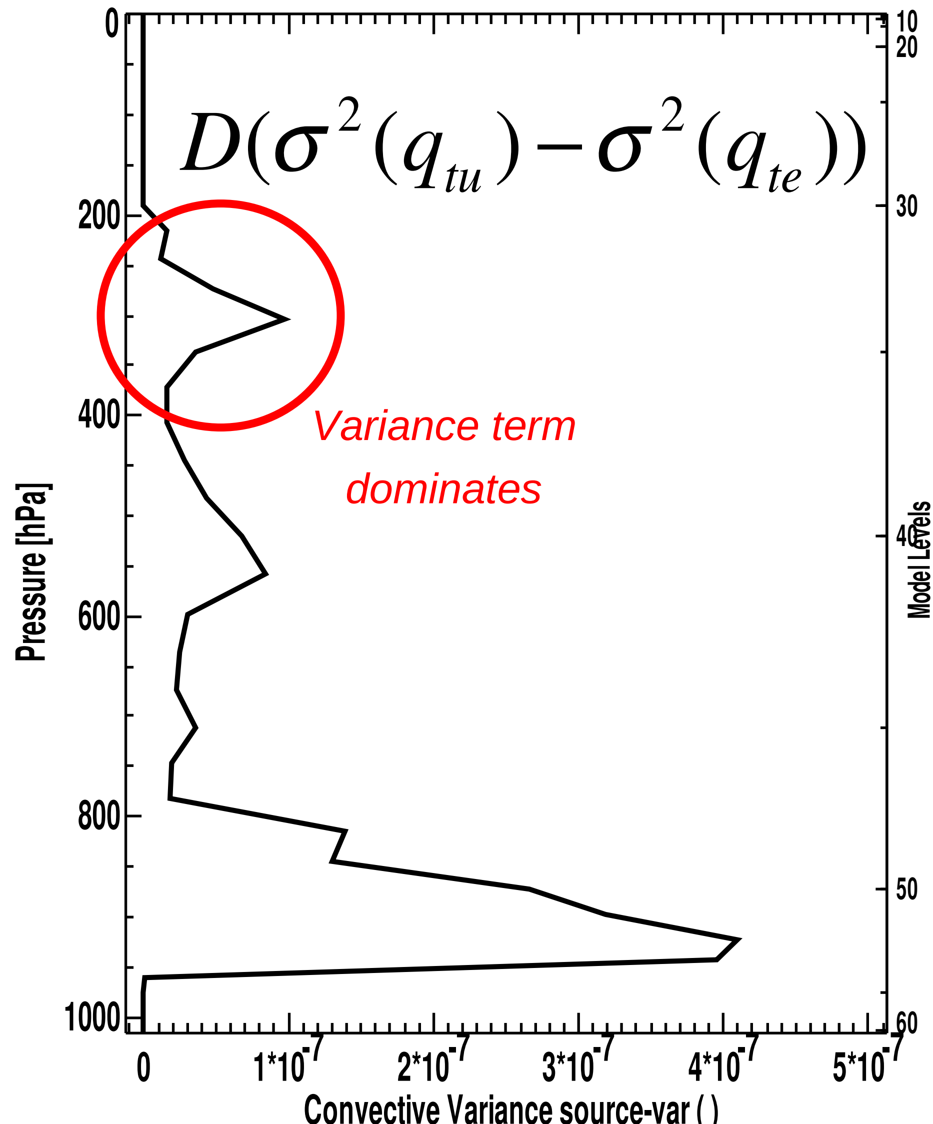
Offline convective updraft variance



Convection source terms comparable

as seen in the CRM results of *Klein et al. 2005*





Microphysics

- Change in variance

$$\overline{P'q_t'}$$

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

$$P = Kq_l^{\ n}$$

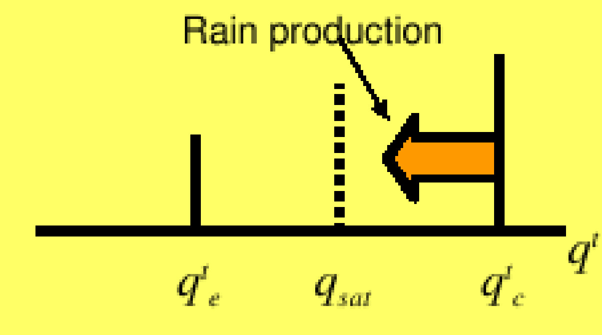
$$P = Kq_l(1 - e^{-(\frac{ql}{qlcrit})})$$

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

$$\int_{q_t = q_{sat}}^{q_{t\_\max}} P' q_t' G(q_t) dq_t$$

Microphysics - Double delta function

No variance cloud or clear sky areas:



Double Delta PDF

$$\sigma^2(q_t) = Cq_c^{t\,2} + (1-C)q_e^{t\,2} - q^{t\,2}$$

And:

$$q^t = Cq_c^t + (1-C)q_e^t$$

$$\left.\frac{\partial q_e^t}{\partial t}\right|_{\mathrm{micro}} = 0, \qquad \left.\frac{\partial C}{\partial t}\right|_{\mathrm{micro}} = 0$$

gives:

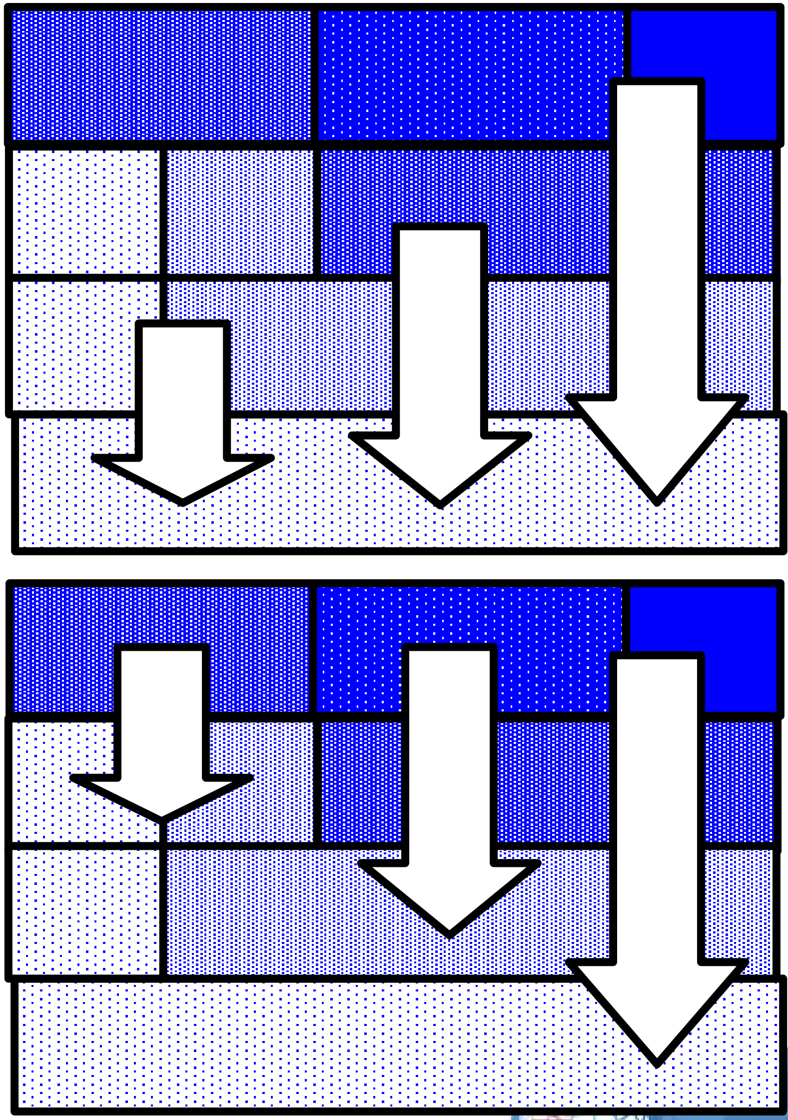
$$\left.\frac{\partial \sigma^2(q^t)}{\partial t}\right|_{micro} = C(1-C)(2q_c^t - q_e^t)\frac{\partial q_c^t}{\partial t}$$

Berry Sundqvist

$$\frac{\partial q_c^t}{\partial t} = F(q_c^t) \quad \text{E.g.} \quad \frac{\partial q_c^t}{\partial t} = -K(q_c^t)^N, -Kq_c^t(1-\exp[-(q_c^t / q_{crit}^t)^2]),\ldots$$

but can get very complicated...

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



Summary of statistical schemes

- Advantages
  - Information concerning subgrid fluctuations of humidity and cloud water is available
  - It is possible to link the sources and sinks explicitly to physical processes
  - Use of underlying PDF means cloud variables are always consistent
- Disadvantages
  - Deriving these sources and sinks rigorously is hard, especially for higher order moments needed for more complex PDFs!

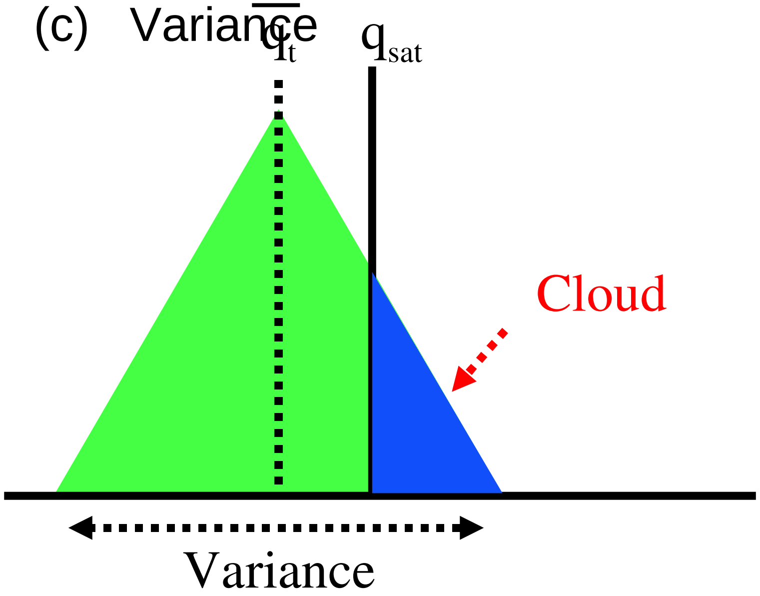
Which prognostic equations?

Take a *2 parameter distribution* & partially cloudy conditions

Can specify distribution with total water:

(b) Mean

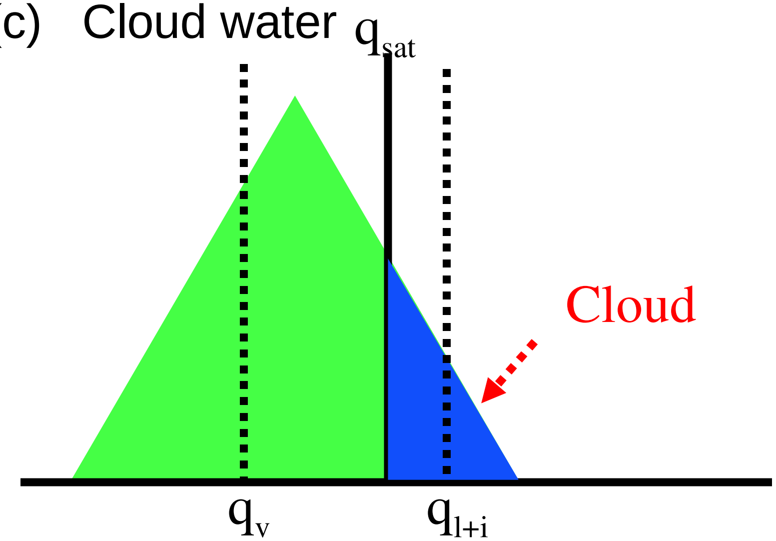
(c) Variance



Can specify distribution with mass mixing ratio of

(b) Water vapour

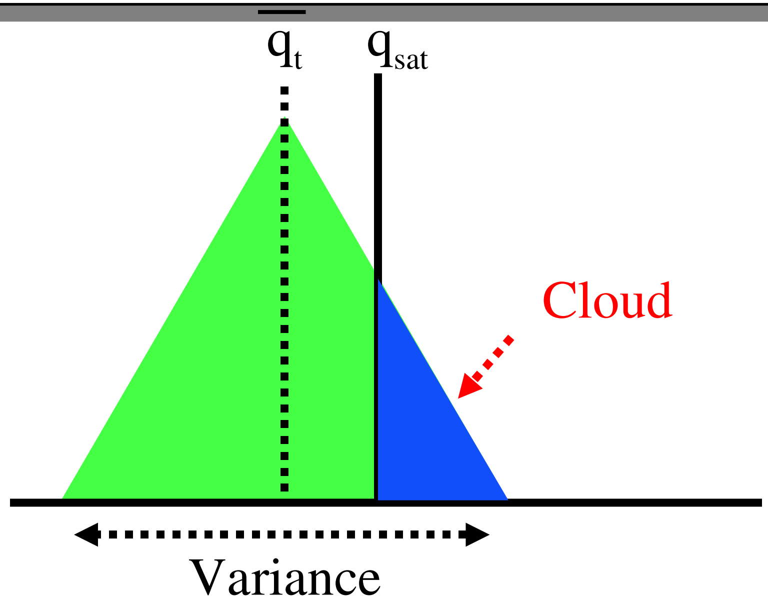
(c) Cloud water



Implication: Most models have separate cloud water and vapour prognostic equations.

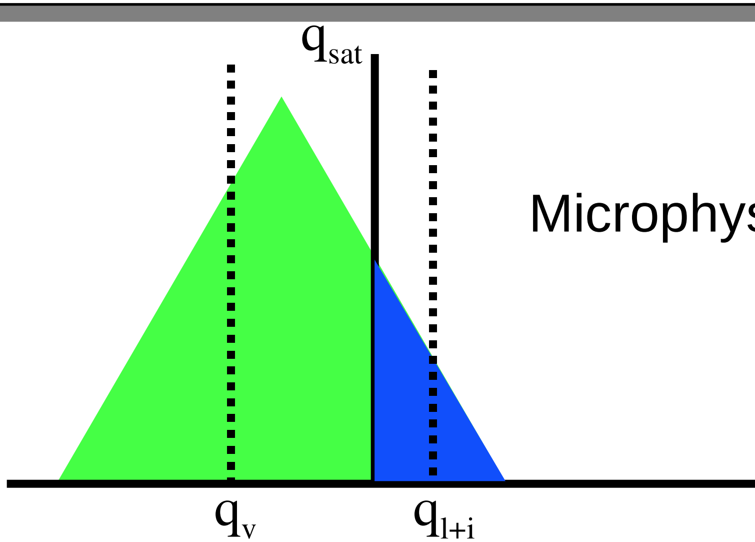
The addition of a prognostic variance equation implies problem overspecified

Prognostic PDF moments (variance, skewness...)



- PDF always defined, but need to parametrize those tricky microphysics terms

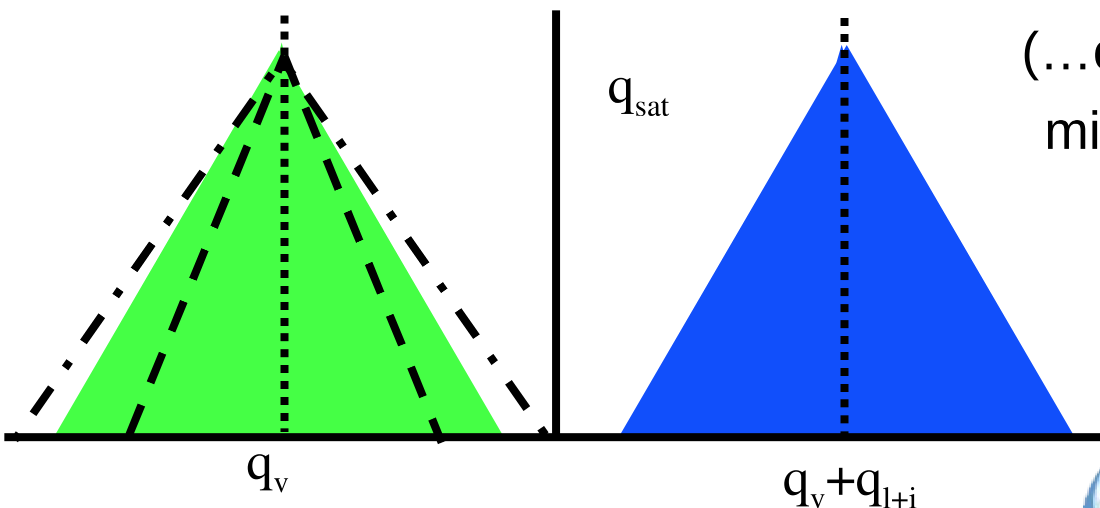
Prognostic cloud/vapour



Microphysics

But problems arise in

Clear sky conditions (turbulence)



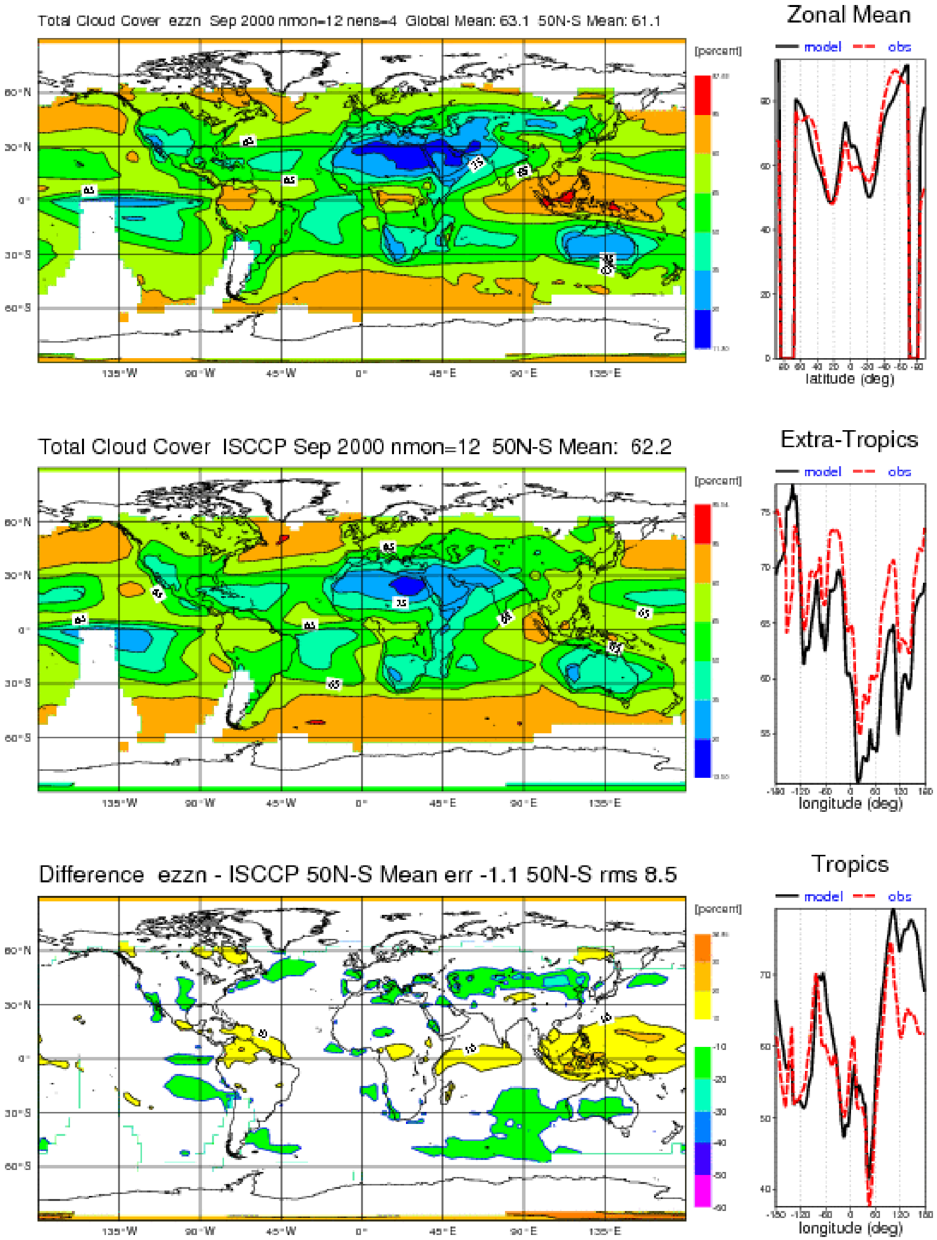
Overcast conditions (…convection + microphysics)

Tiedtke Scheme at ECMWF

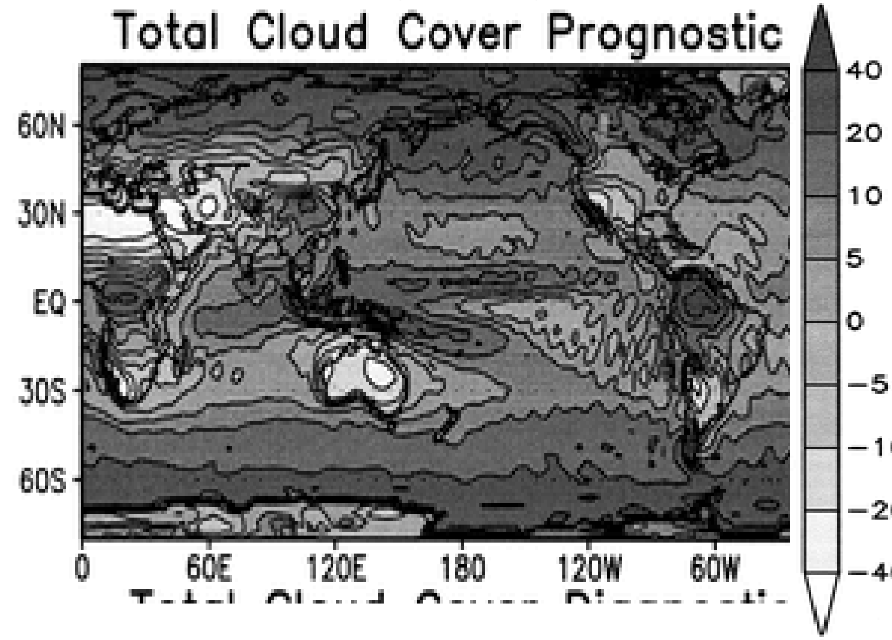
- Tiedtke scheme represents exactly this form of variable translation
- Prognostic equations for
  - Vapour
  - Cloud water
  - Cloud cover
- Sources and sinks can be derived using PDF assumptions
- Lack of memory in clear sky/overcast conditions
  - cloud forms at RH_crit (~80%)
  - no subcloud variability (delta function)

Total cloud cover comparison

33r1



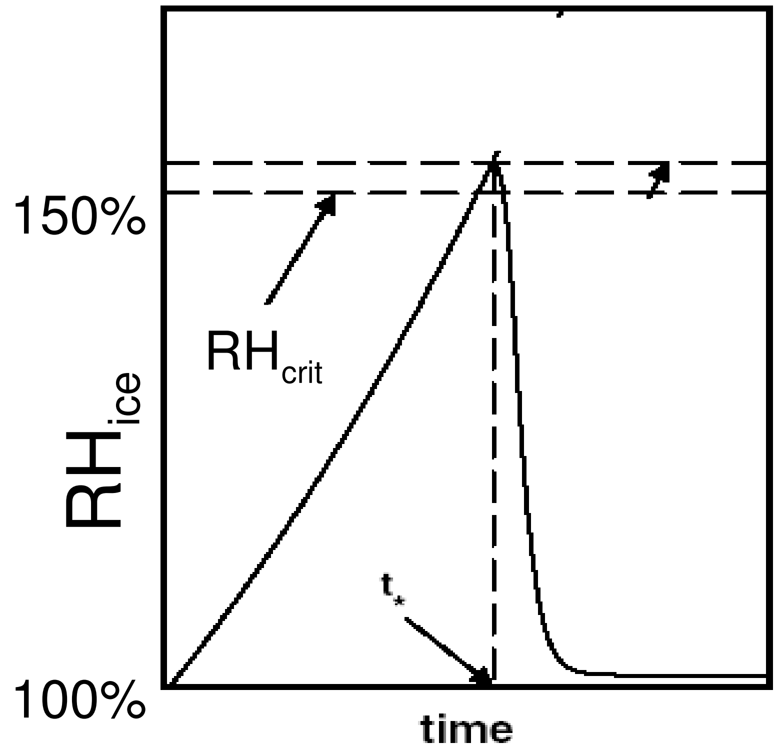
ECHAM5



...difficult to judge scheme on limited parameter range... validation of cloud scheme will be revolutionized by CloudSAT

Ice complications

- Due to relative lack of ice nuclei in the atmosphere, supersaturation with respect to ice is common!
  - Threshold for ice nucleation is not q_s
  - Liquid clouds do not glaciate at 0^oC
- Nucleation and sublimation timescales are not necessarily fast compared to a GCM timestep (depends on N_i)



A parameterization of cirrus cloud formation: Homogeneous freezing of supercooled aerosols

B. Kärcher
Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

U. Lohmann
Atmospheric Science Program, Department of Physics, Dalhousie University, Halifax, Nova Scotia, Canada

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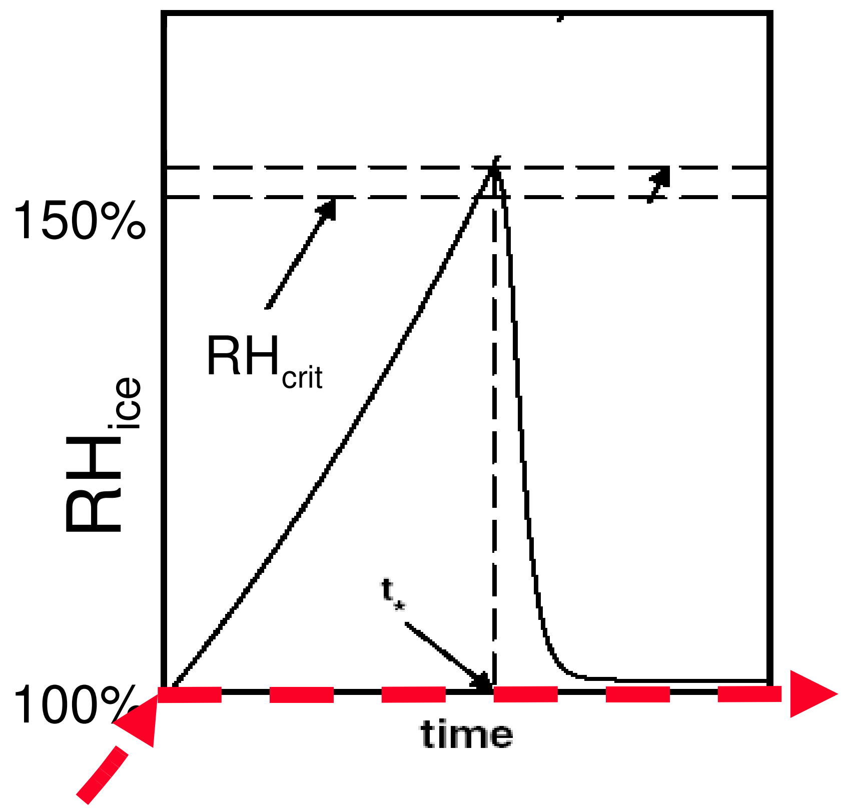

ECMWF current operations

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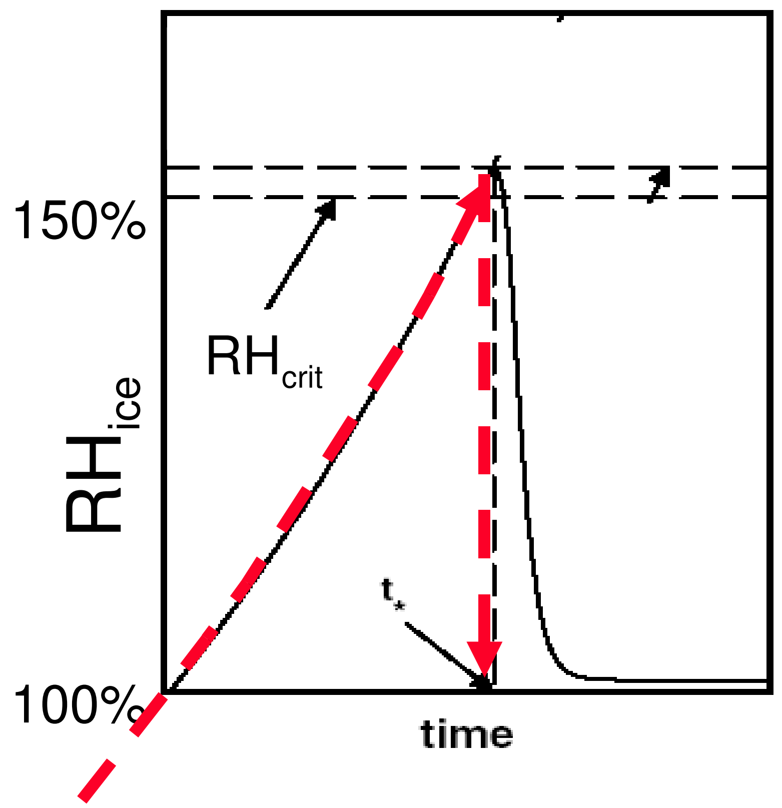
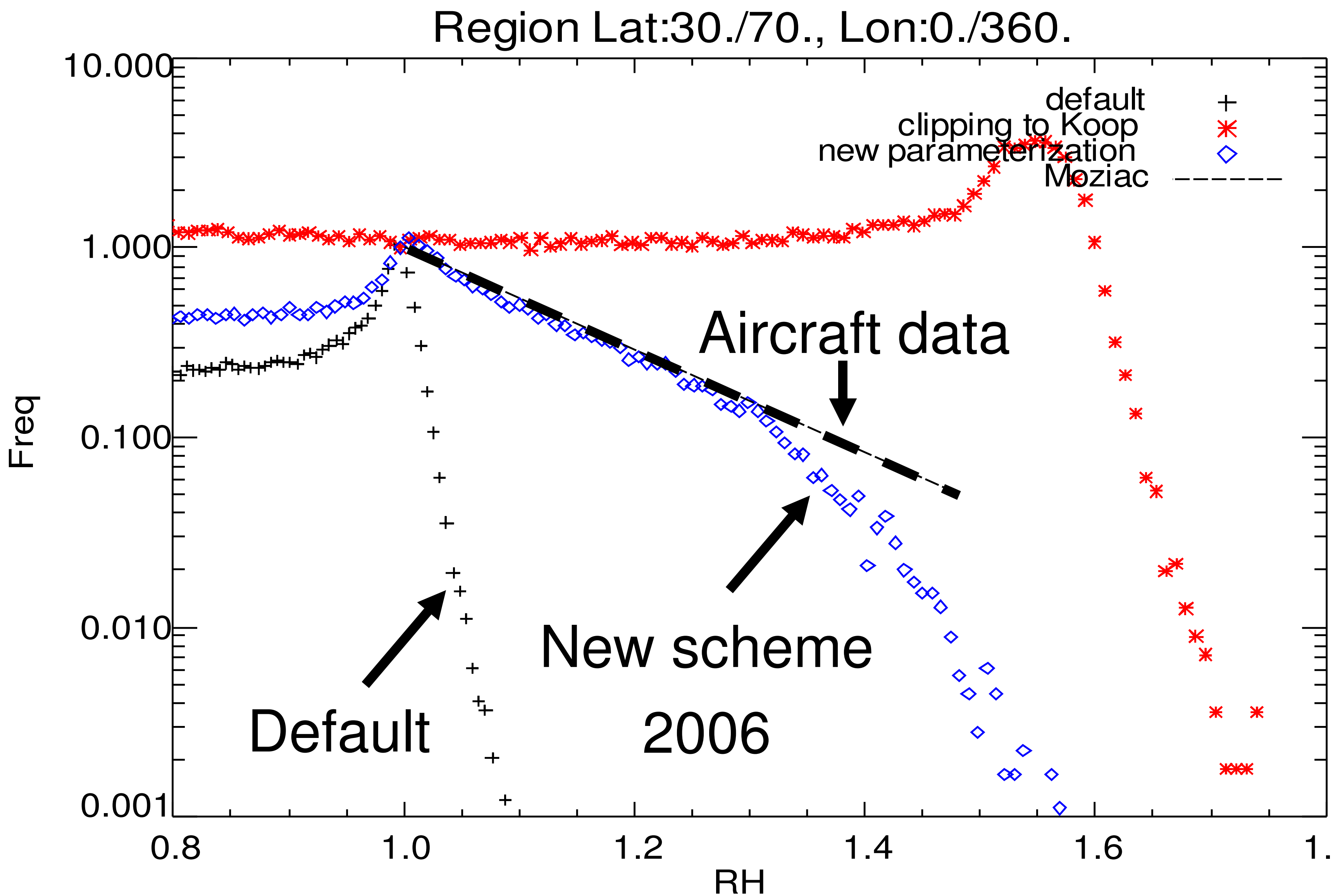


Threshold allowed
but no nucleation timescale

ECMWF > 2006

Simple ECMWF scheme: comparison to Mozaic aircraft data



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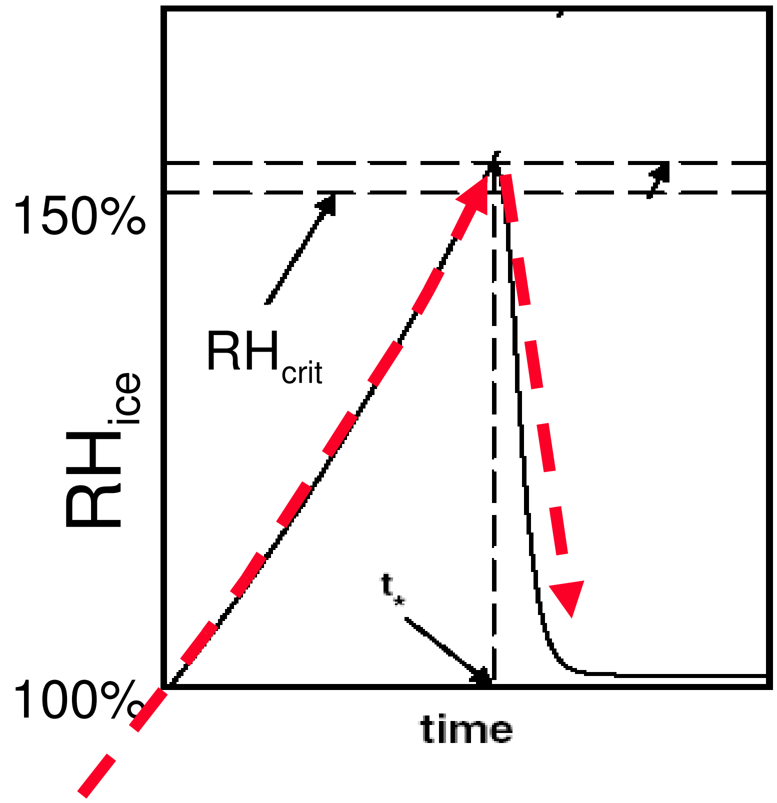
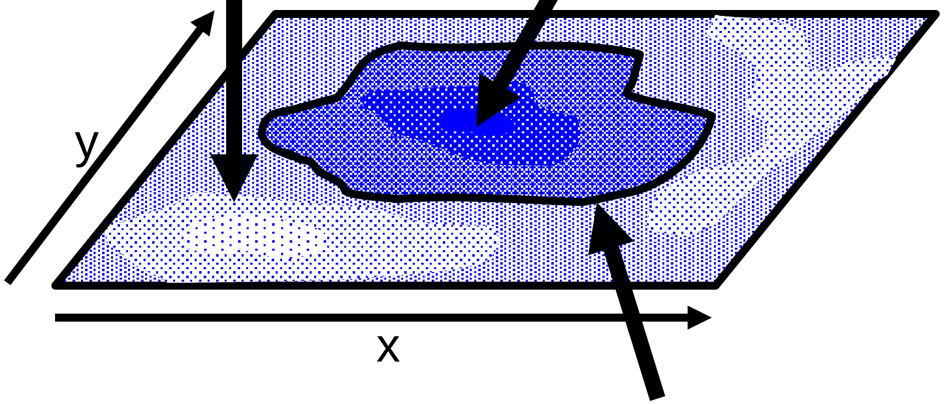


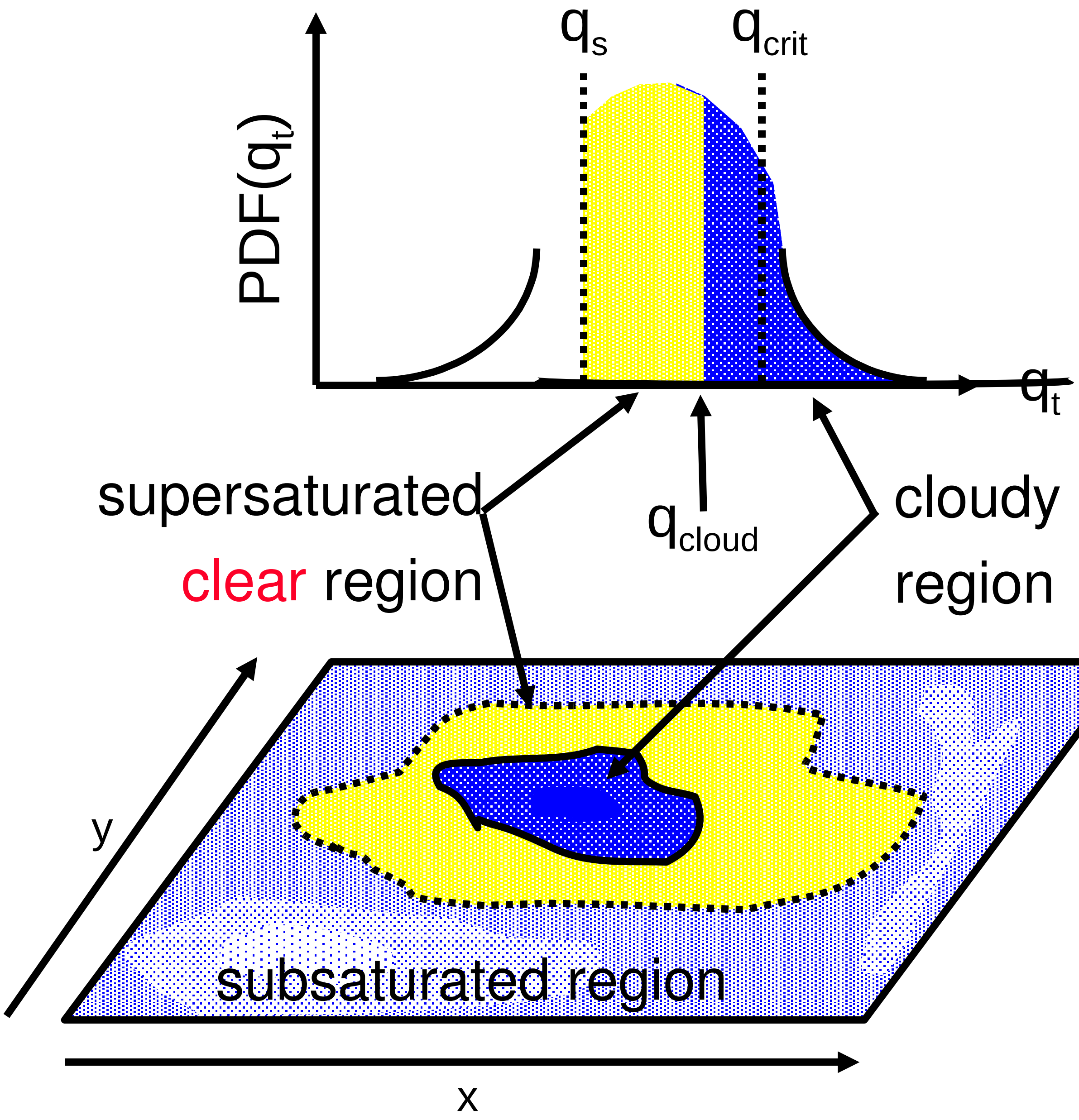
full scheme, nice but requires…

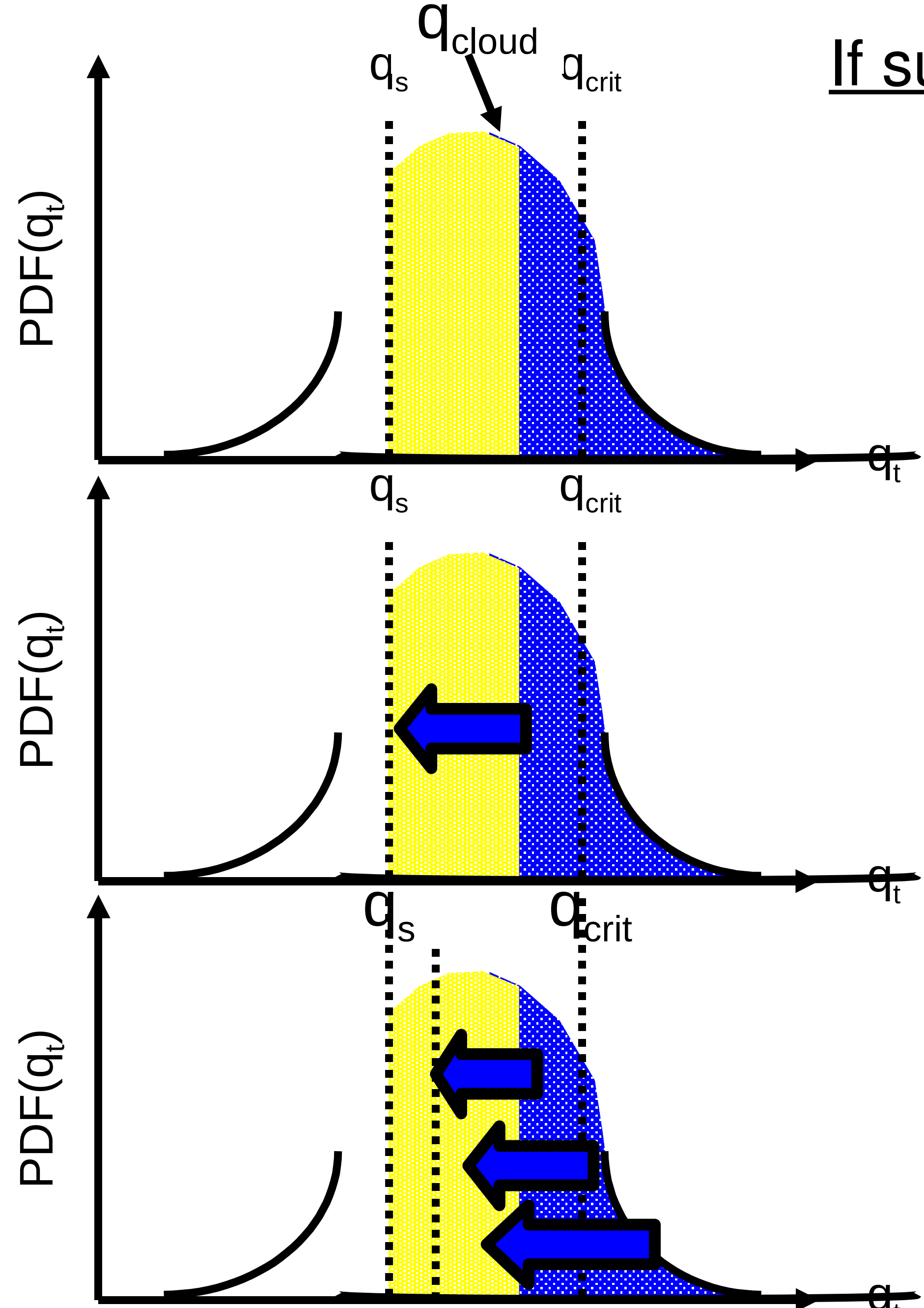
requires... more prognostic parameters!!!



- q_v needed separately in and out of cloud since nucleation only affects cloudy area, while supersaturation in both regions is allowed
- Calculation of C requires knowledge of this process!

Statistical scheme framework, identical considerations!





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

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

If assume fast adjustment, derivation is straightforward

$$q_i = \int_{q_{cloud}}^{\infty} (q_t - q_s) PDF(q_t) dq_t$$

Much more difficult if want to integrate nucleation equation explicitly throughout cloud

Hybrid Approach?

- Warm clouds suited to PDF approach (total water is vapour+liquid)
- Ice clouds suited to Tiedtke approach
  - Ice particles not in suspension
  - Ice does not form at set threshold
- Approach of met office to have separate ice and liquid cloud fractions?
  - PDF scheme=liquid, Tiedtke scheme=ice
- Combining them with a random overlap assumption?

Current developments at ECMWF

- 5-phase bulk prognostic scheme with implicit numerics
- Implicit framework with prognostic: vapour - rain - liquid cloud - snow - ice
- With minimum changes to microphysics
- *Richard Forbes*: CloudSAT used for scheme development, tuning and validation

Summary

- Cloud parametrization can be divided into microphysics and for coarse scale models geometry

  see Richard's talk

- Geometry refers to partial cloud fraction – complicated by the fact that some condensates have non-zero fall speeds, thus cloud overlap and structure important (but also for radiation).
- Partial cloud fraction only possible if subgrid-scale variability of water/temperature exists
- This implies that PDF-based approaches are applicable; these explicitly model the nature of the subgrid-scale fluctuations (ECHAM5 prognostic scheme implemented but adhoc)
- However, condensates fall! Complicates matters again – PDF approach appropriate for (local) warm clouds, separate ice cloud fraction required?