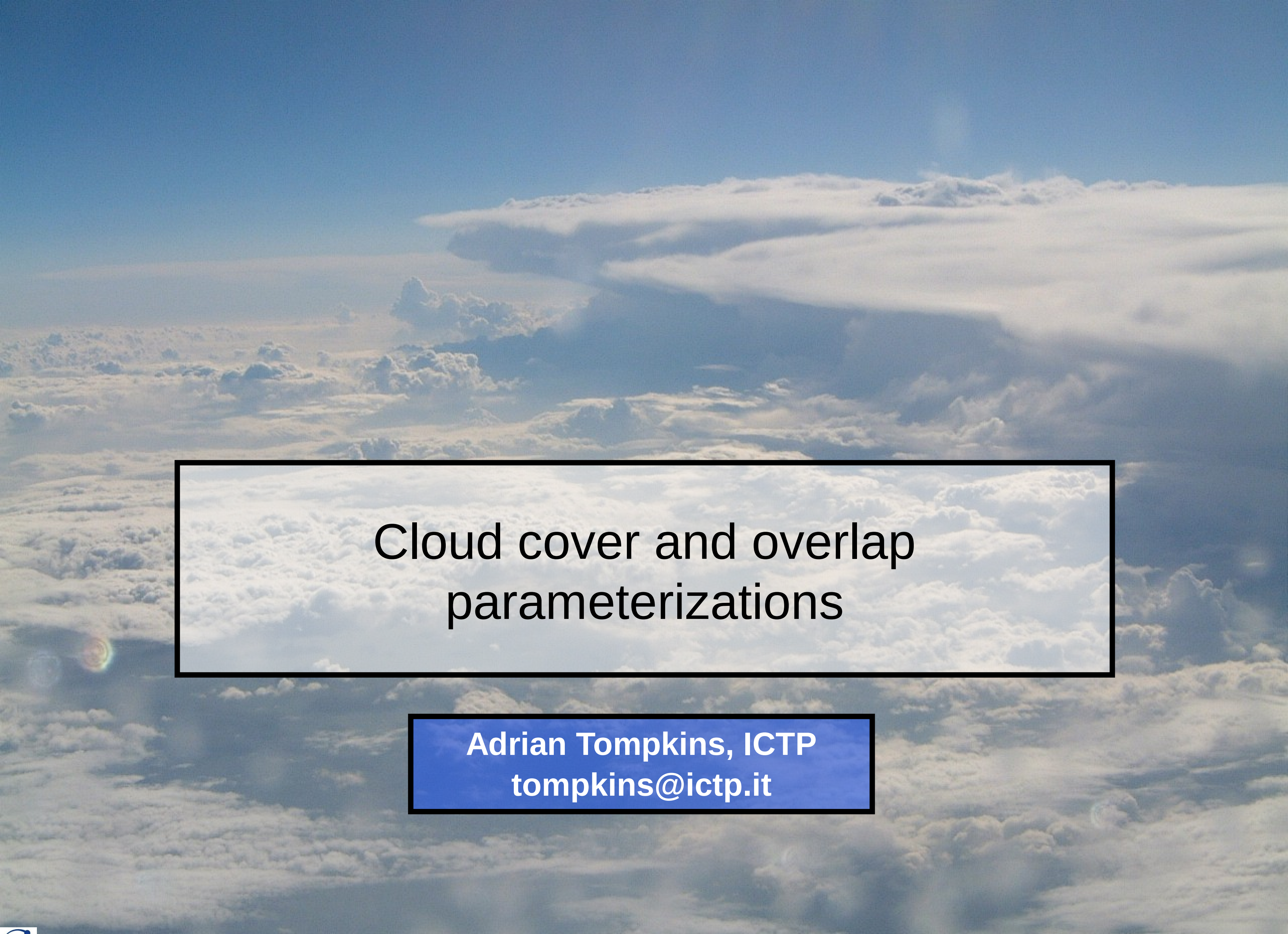
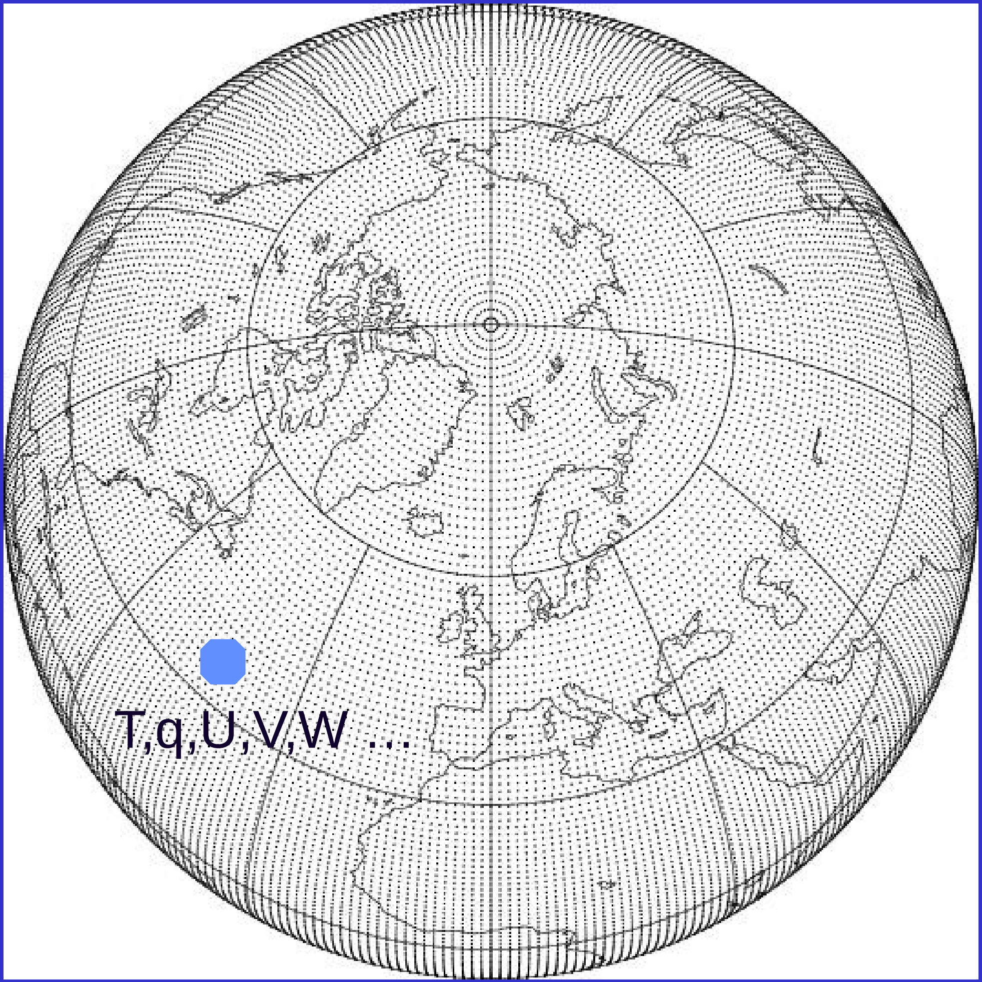


Cloud cover and overlap parameterizations

Adrian Tompkins, ICTP
tompkins@ictp.it

Clouds in General Circulation models=GCMs

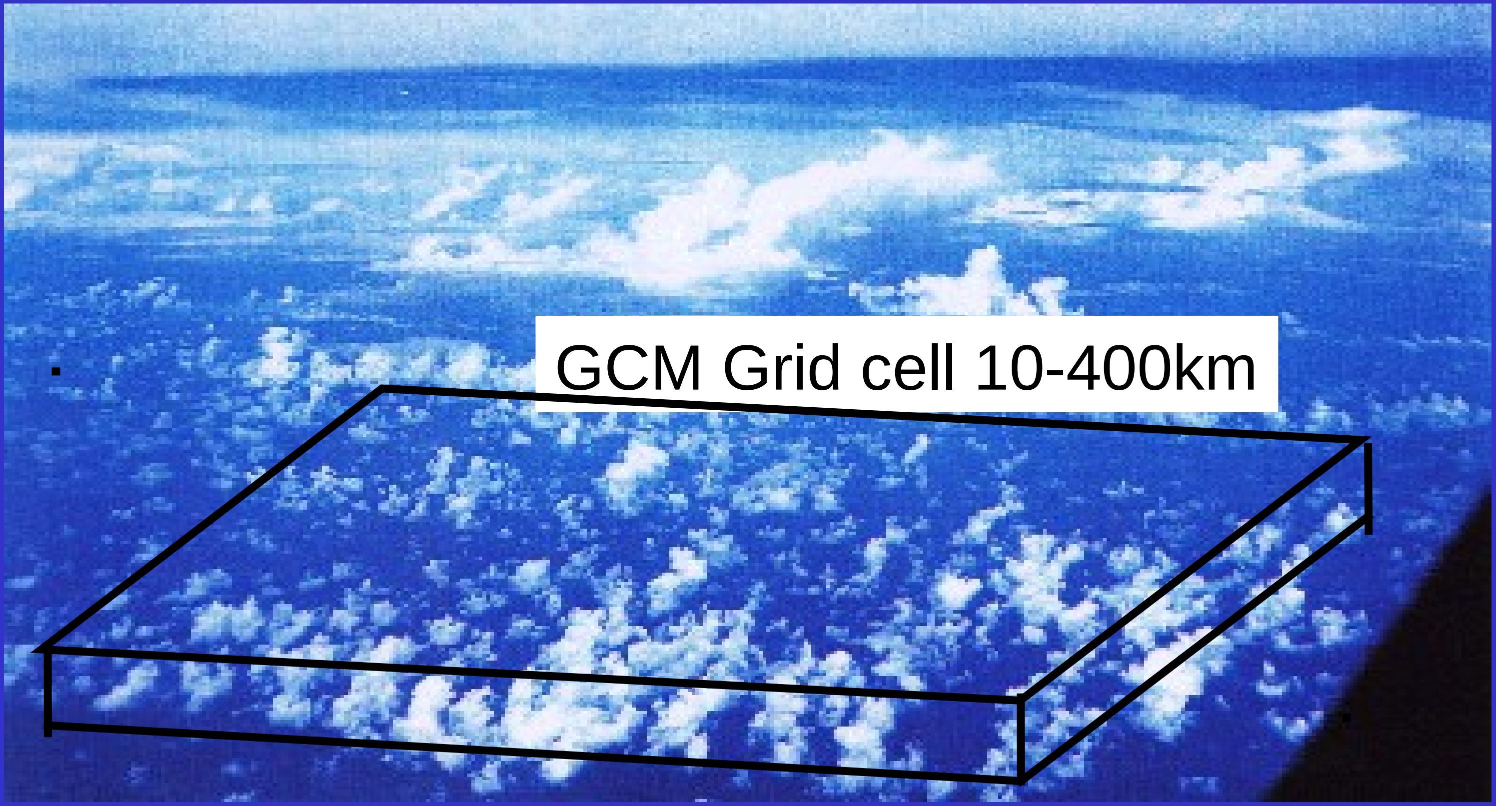


- GCMs describe the equations of motion on a discrete grid
- E.g. ECMWF global forecast model with T1280 spectral resolution (~9km equivalent) with 137 vertical levels
- Many processes occur on scales smaller than this

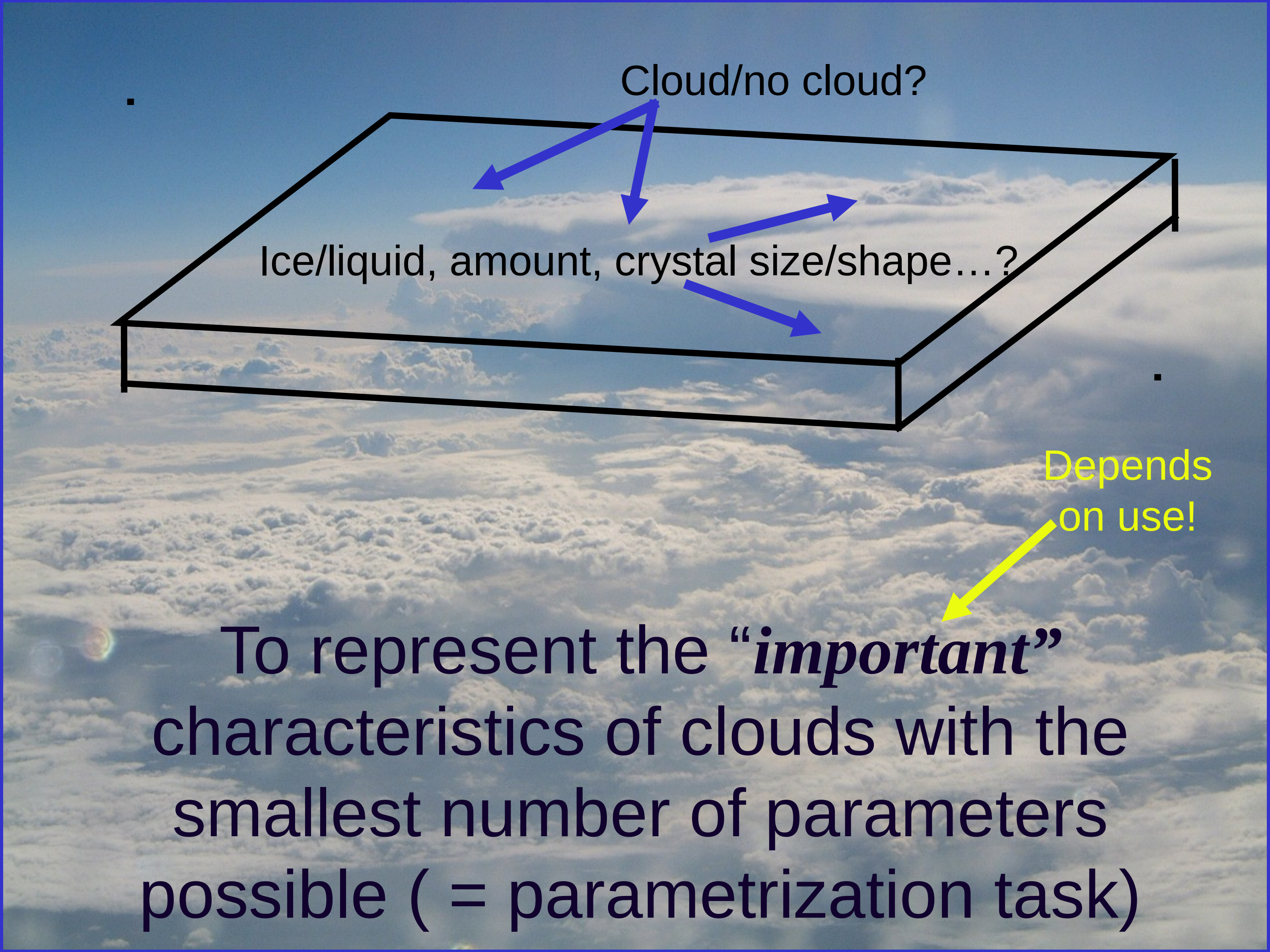
Clouds in GCMs - What are the problems ?

Clouds are subgrid-scale

(both horizontally and vertically)



Clouds in GCMs: The aim



Cloud/no cloud?

Ice/liquid, amount, crystal size/shape…?

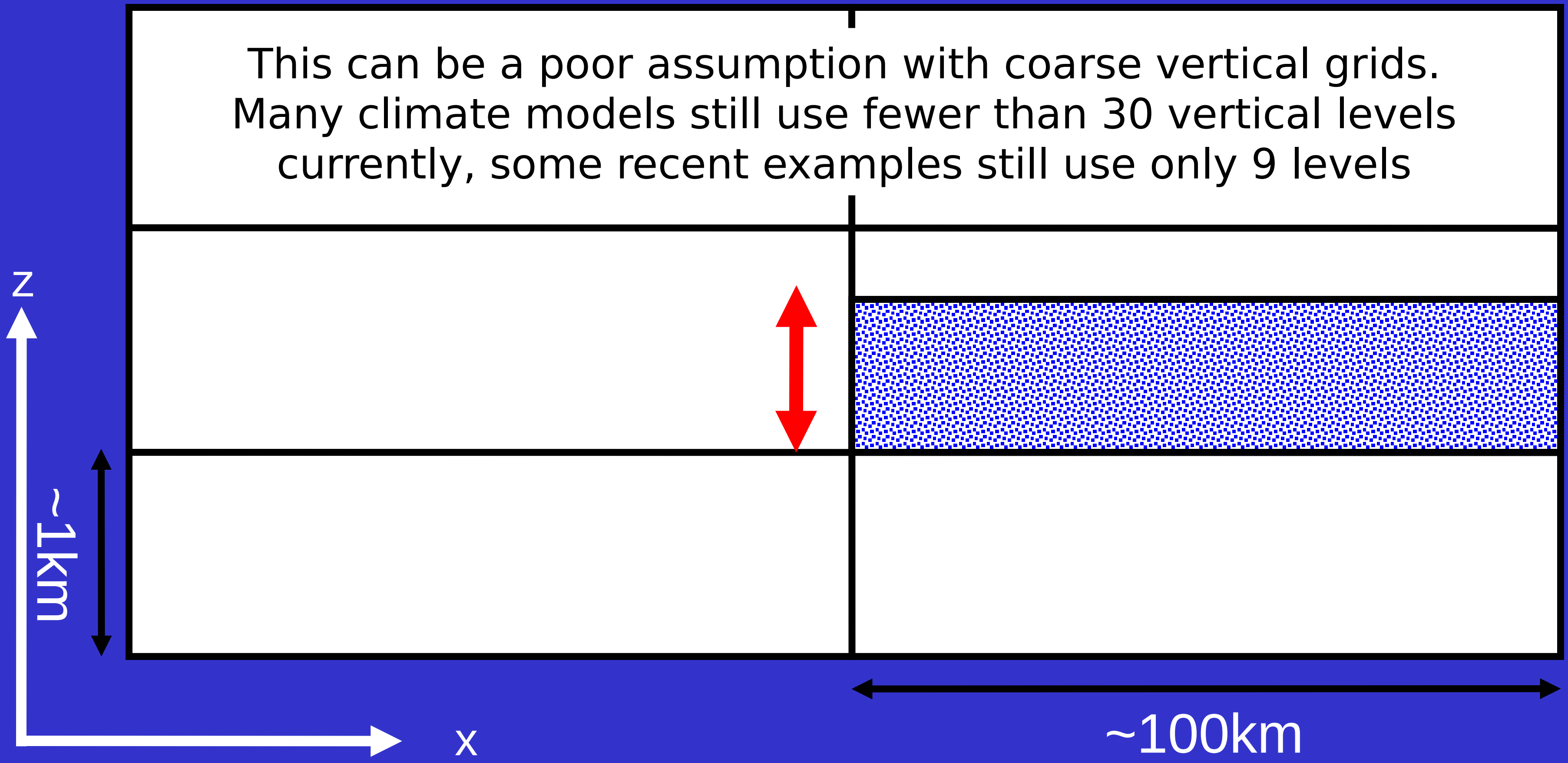
Depends on use!

To represent the “***important***” characteristics of clouds with the smallest number of parameters possible (= parametrization task)

How can we describe clouds? Which characteristics?

VERTICAL COVERAGE

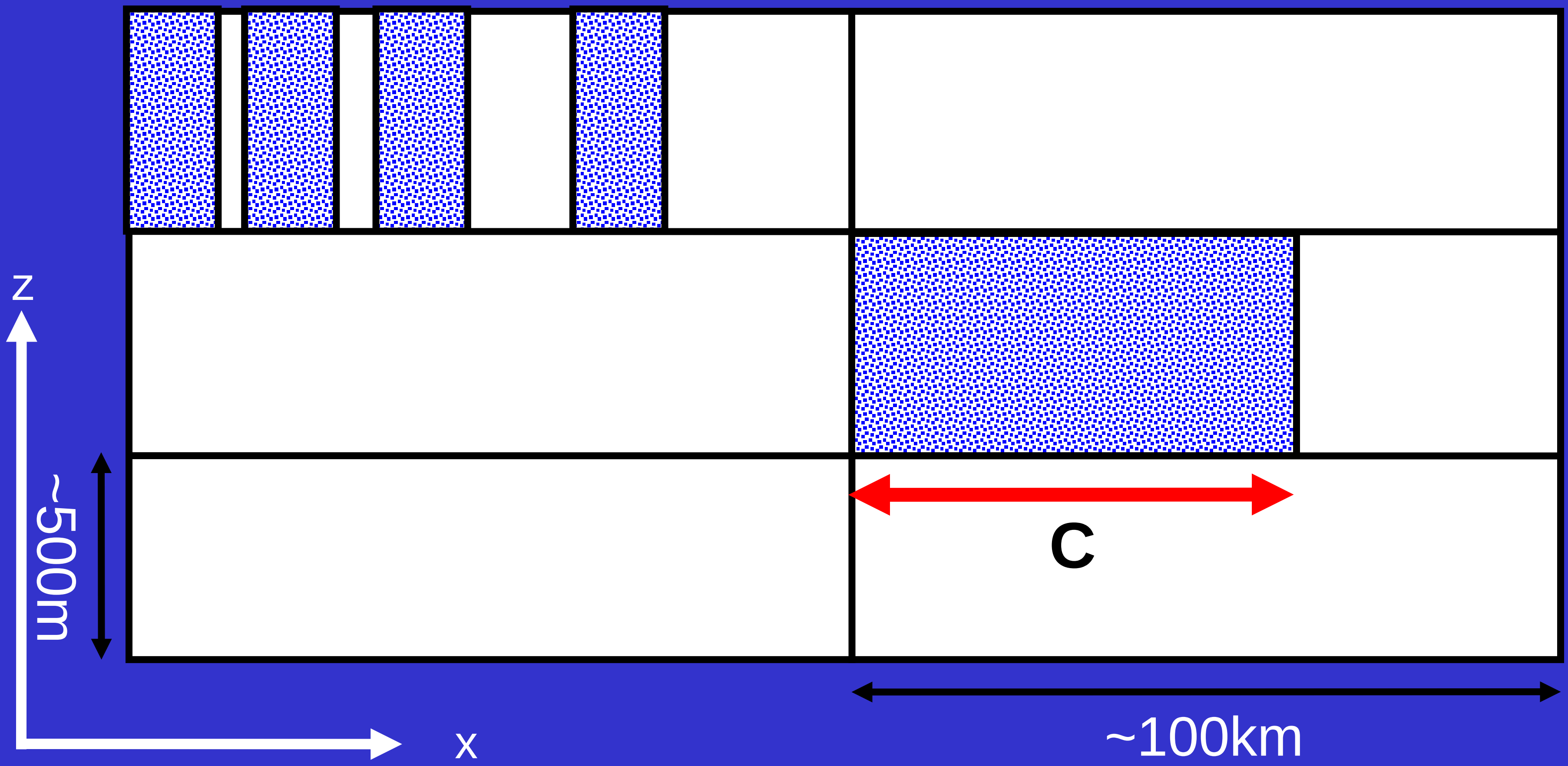
Most models assume that this is 1



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?

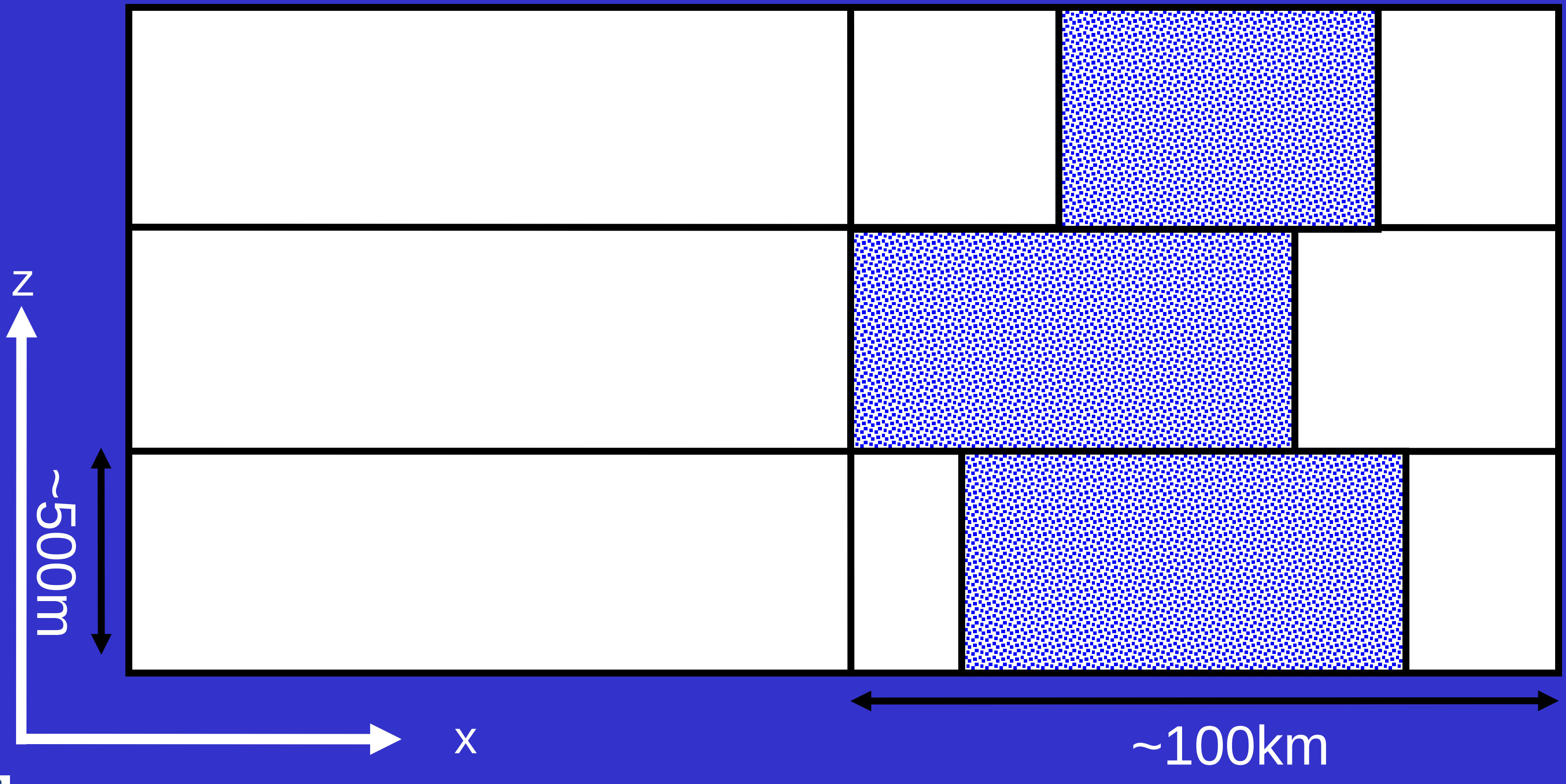
HORIZONTAL COVERAGE, C
Spatial arrangement?



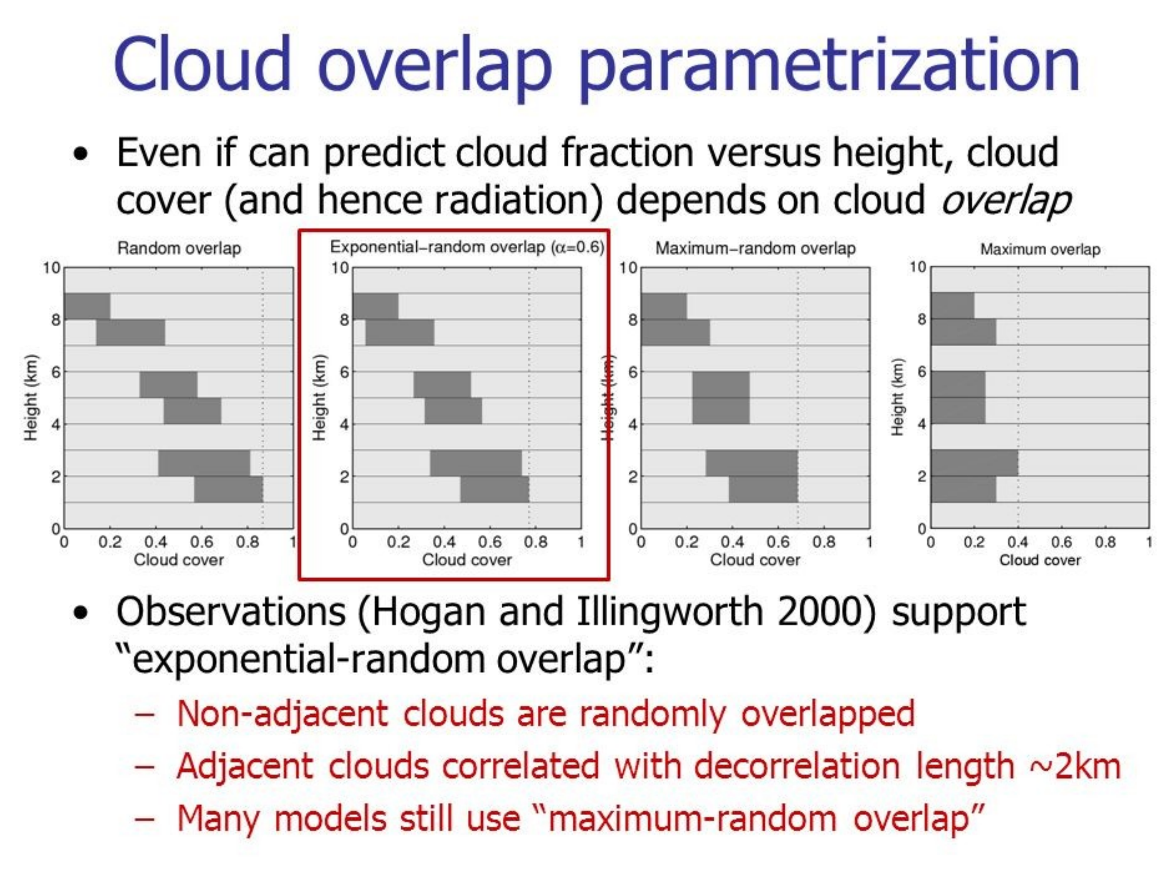
How can we describe clouds? Which characteristics?

VERTICAL OVERLAP OF CLOUD

Important for Radiation and Microphysics Interaction



Overlap approaches

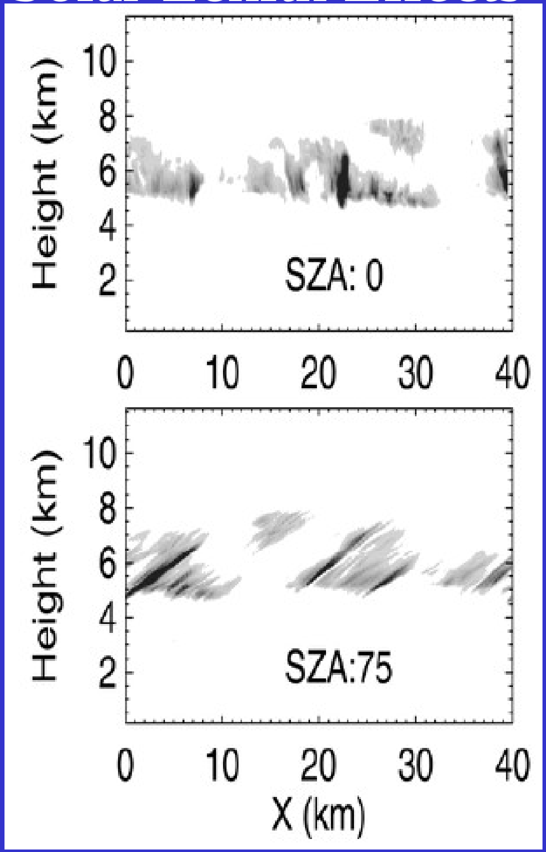


Cloud overlap parametrization

- Even if can predict cloud fraction versus height, cloud cover (and hence radiation) depends on cloud *overlap*

- Observations (Hogan and Illingworth 2000) support "exponential-random overlap":
  - Non-adjacent clouds are randomly overlapped
  - Adjacent clouds correlated with decorrelation length ~2km
  - Many models still use "maximum-random overlap"

Solar Zenith Effects



A. M. Tompkins and F. Di Giuseppe. Generalizing cloud overlap treatment to include solar zenith angle effects on cloud geometry. J. Atmos. Sci., 64:2116-2125, 2007

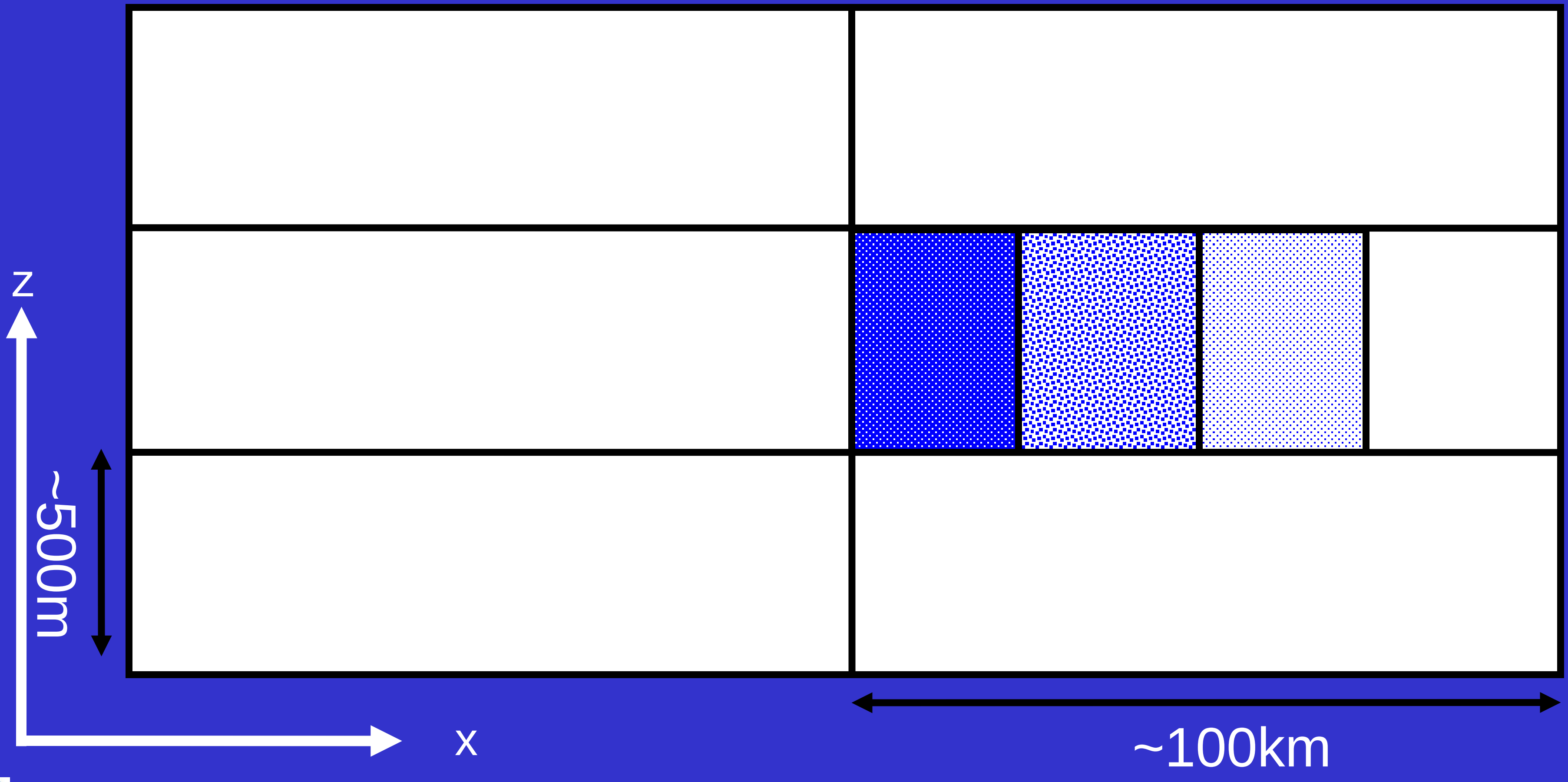
A. M. Tompkins and F. Di Giuseppe. An interpretation of cloud overlap statistics. J. Atmos. Sci., 72:2877-2889, 2015

F. Di Giuseppe and A. M. Tompkins. Generalizing cloud overlap treatment to include the effect of wind shear. J. Atmos. Sci., 72:2865-2876, 2015

How can we describe clouds? Which characteristics?

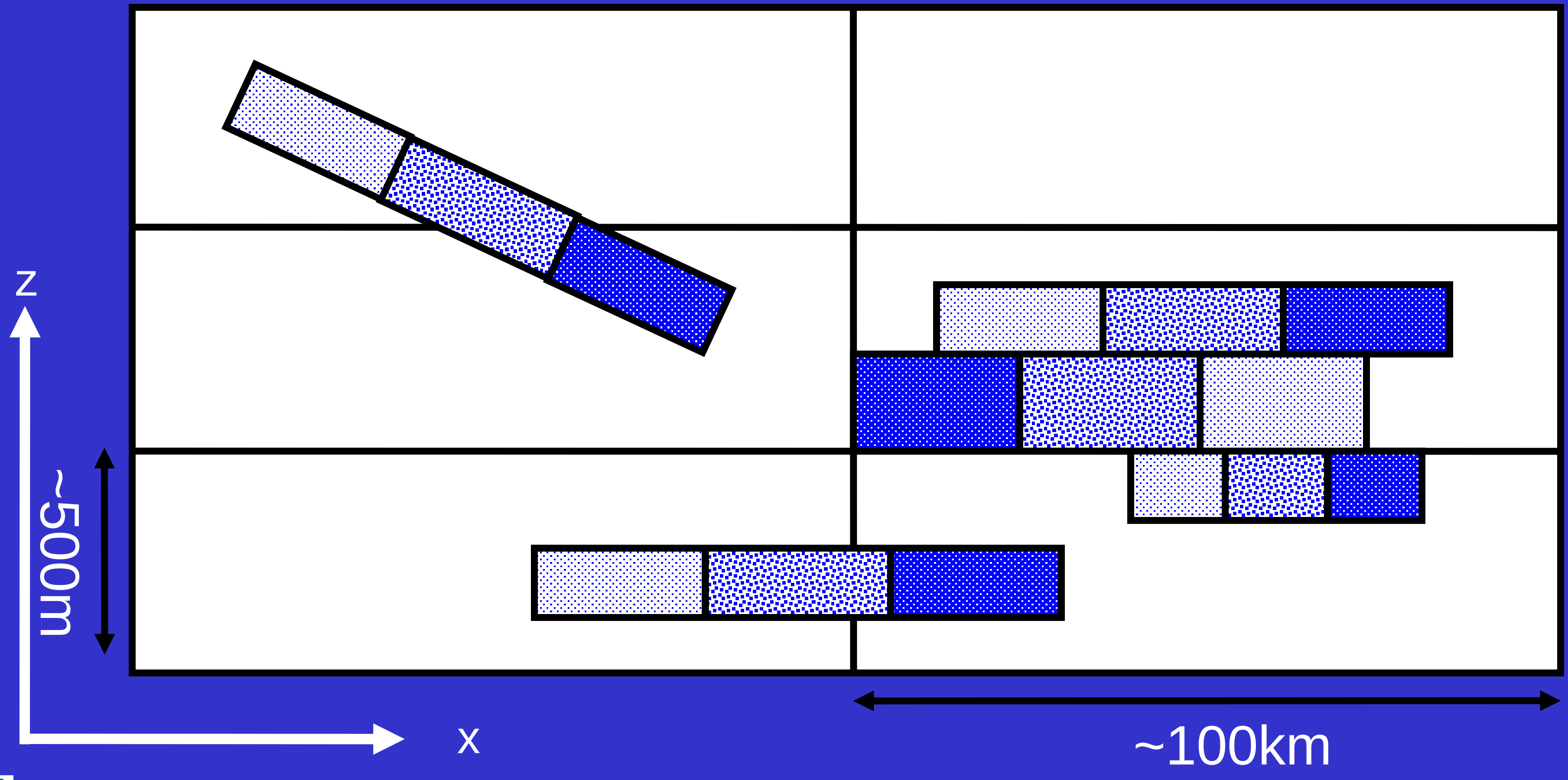
IN-CLOUD INHOMOGENEITY

in terms of cloud particle size and number

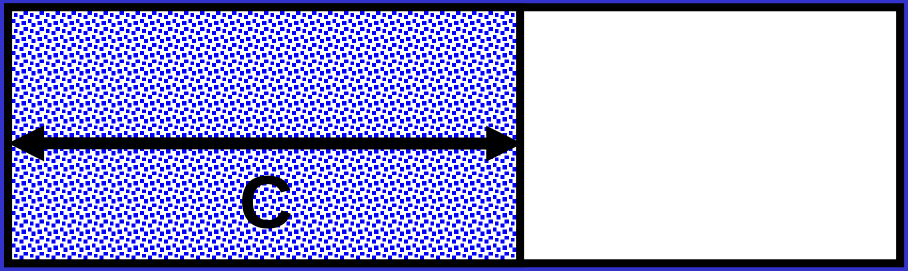


Macroscale Issues of Parameterization

Just these issues can become a little complex!!!



This talk will concentrate on how GCMs represent horizontal cloud cover, C



Talk Outline:

1. Simple diagnostic schemes
2. Statistical schemes
3. The current ECMWF scheme
4. Complications with ice

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

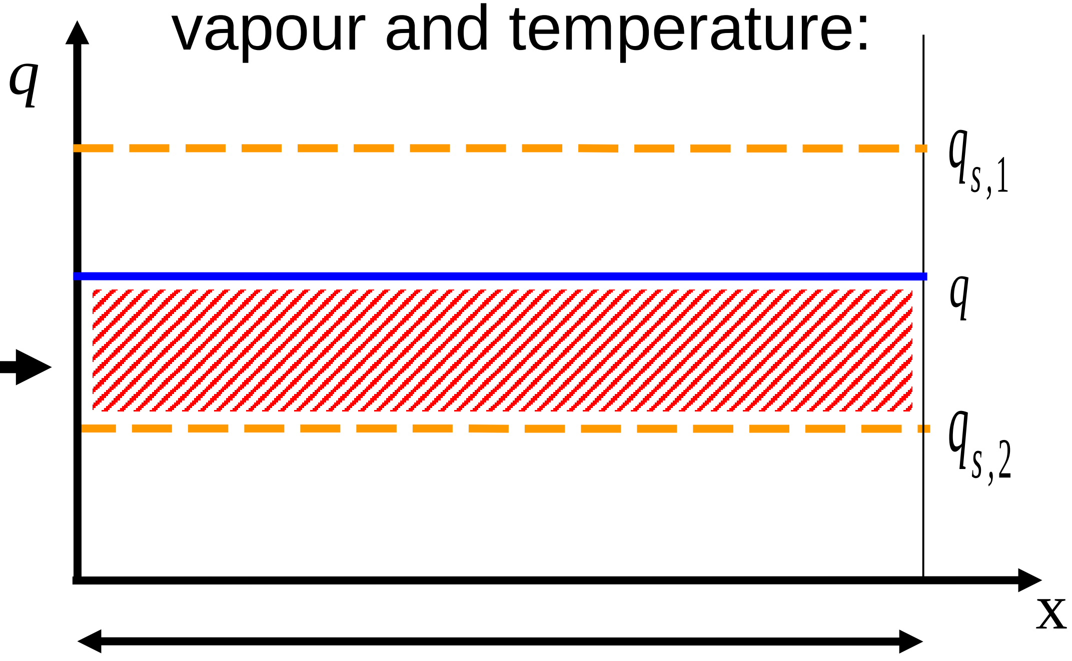
(#2) Condensation process is fast (cf. GCM timestep)

$q_v = q_s$, $q_c = q_t - q_s$

!!Both of these assumptions are suspect in ice clouds!!

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

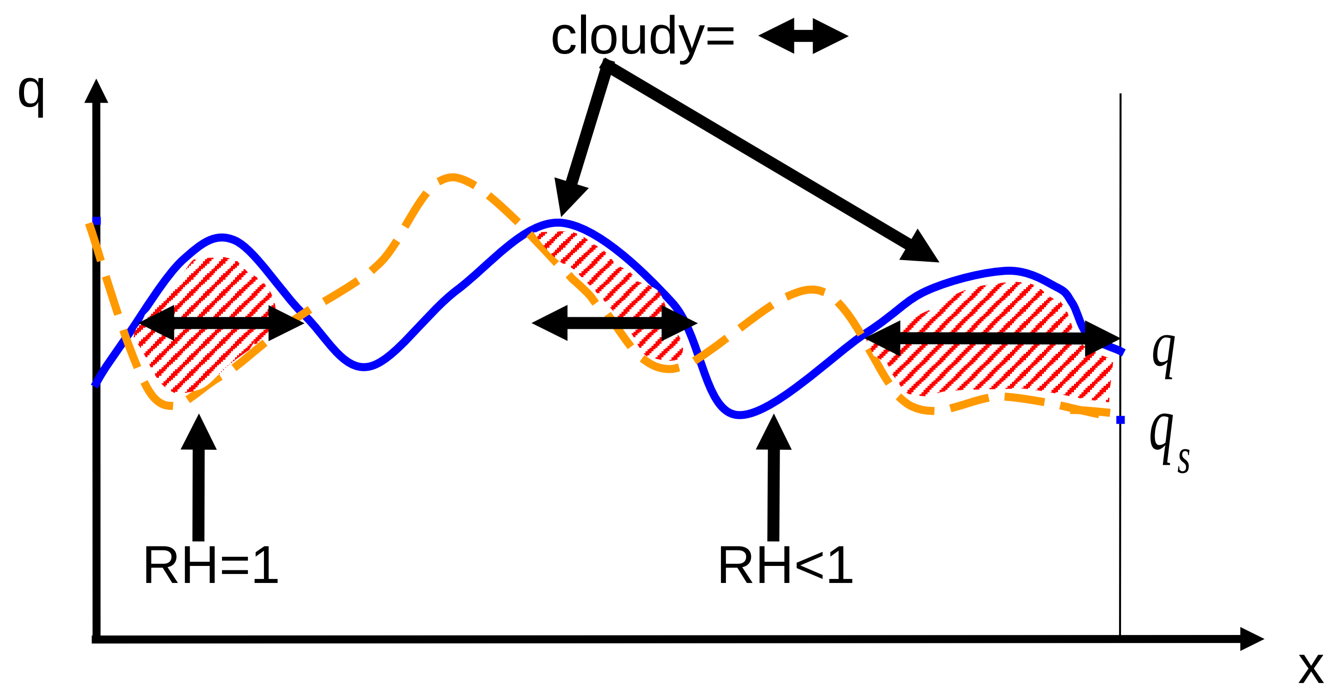
Homogeneous Distribution of water vapour and temperature:



One Grid-cell

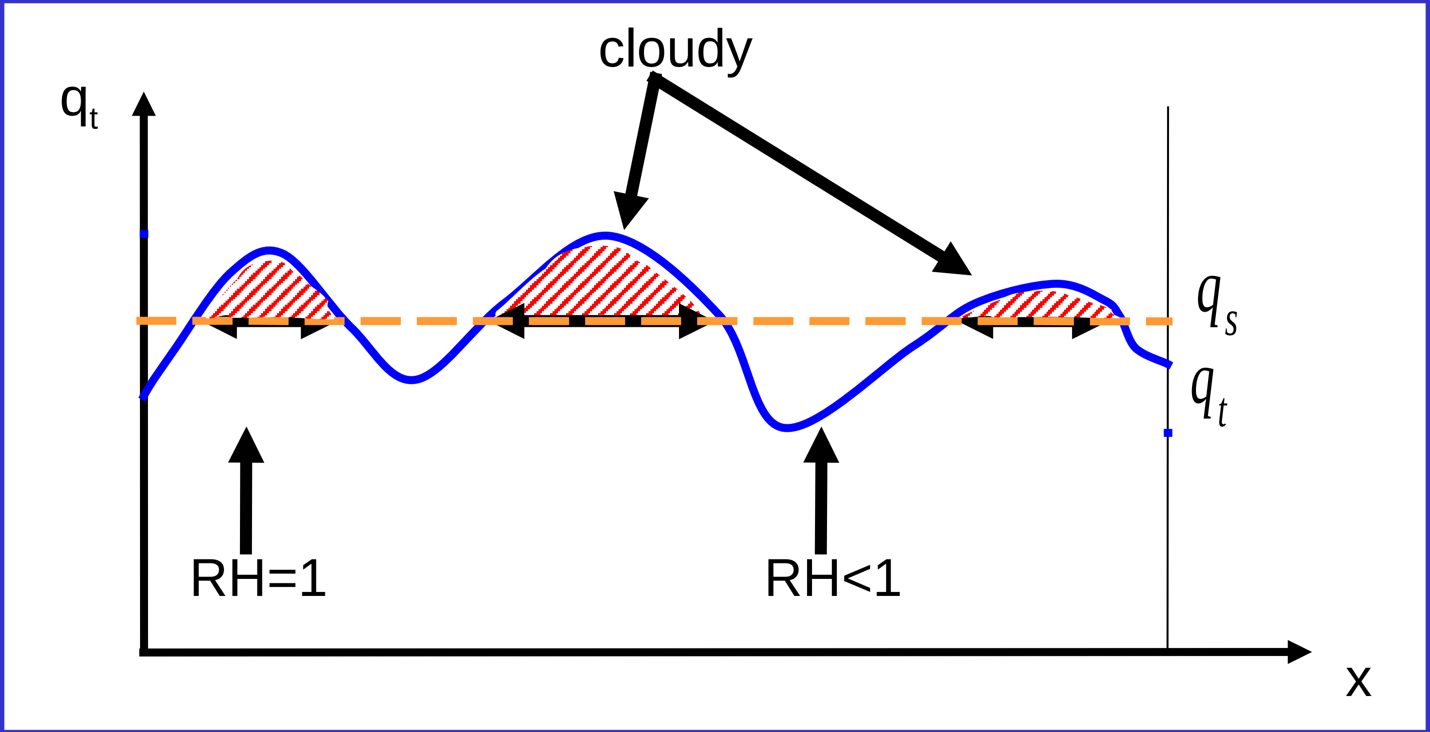
Note in the second case the relative humidity=1 from our assumptions

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

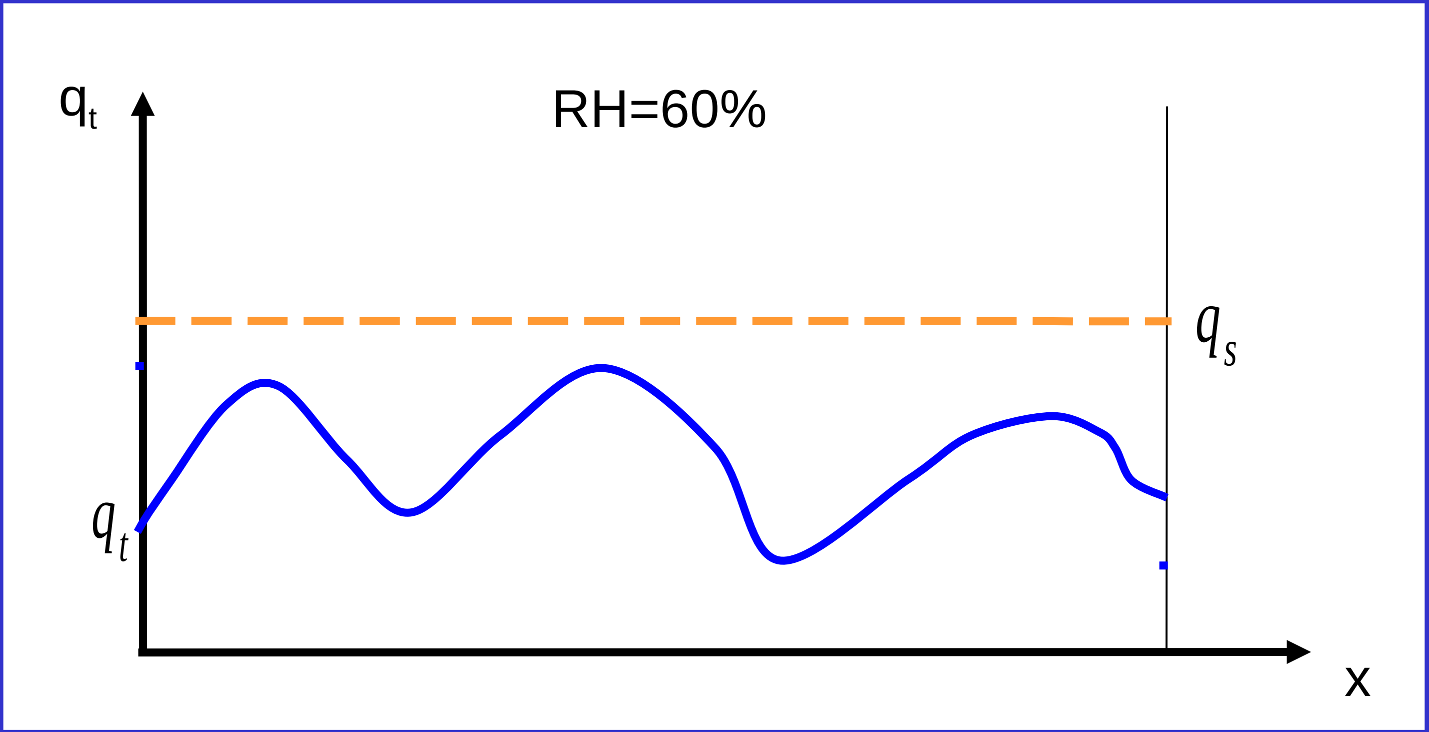


Throughout this talk I will neglect temperature variability

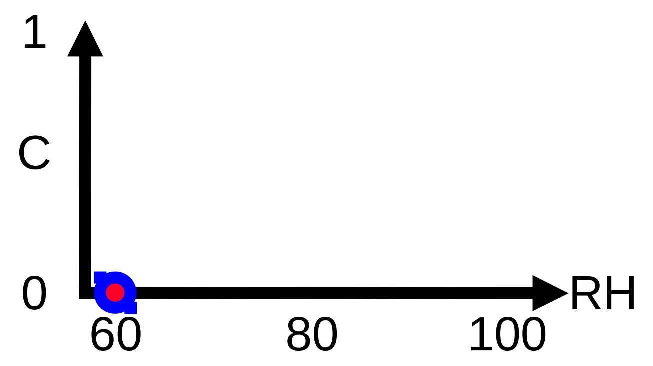
In fact : Analysis of observations and model data indicates humidity fluctuations are more important

#1 Simple Diagnostic Schemes

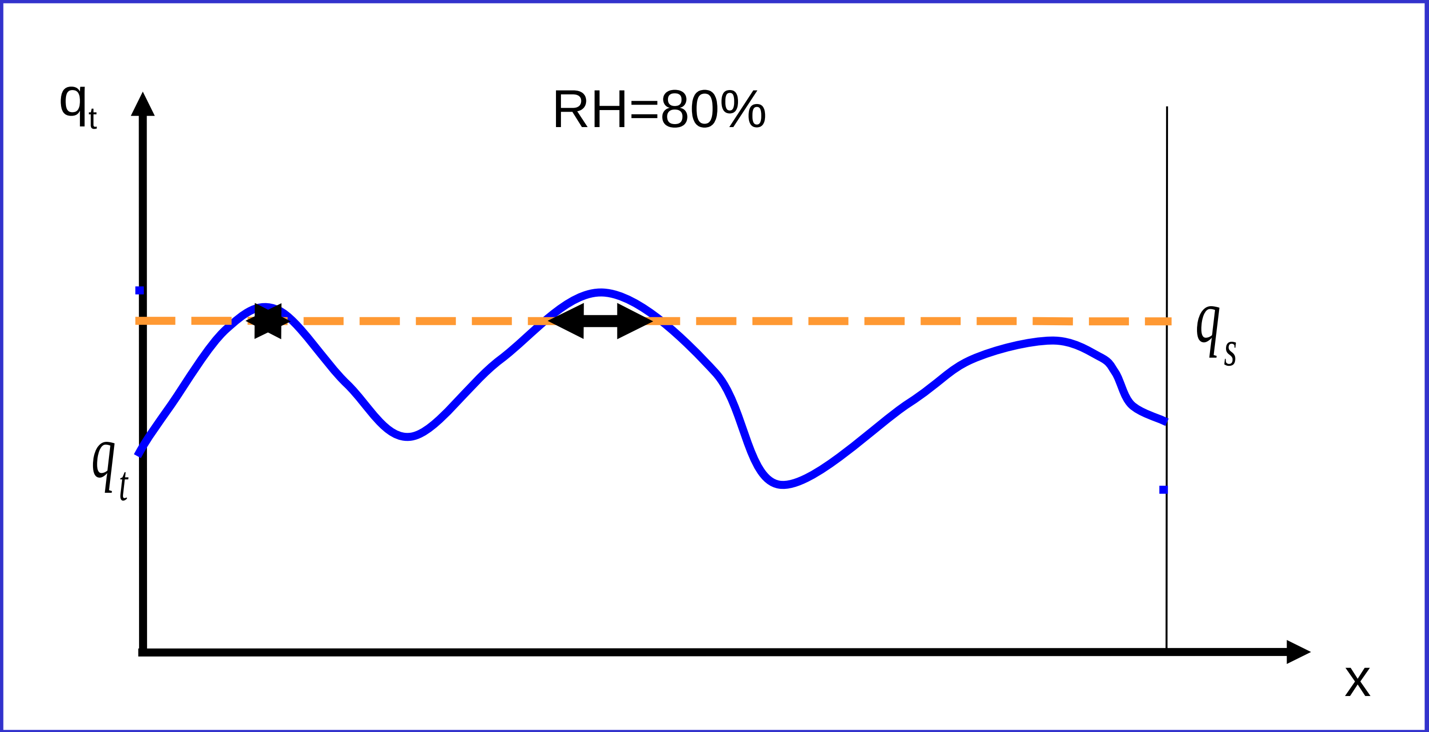
#1 Simple diagnostic schemes: RH-based schemes



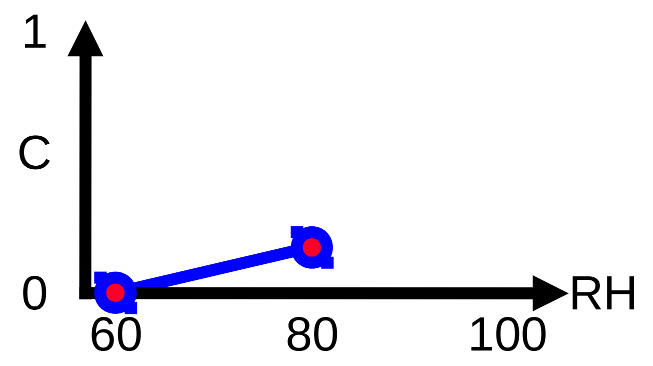
Take a grid cell with a certain (fixed) distribution of total water.
At low mean RH, the cloud cover is zero, since even the moistest part of the grid cell is subsaturated



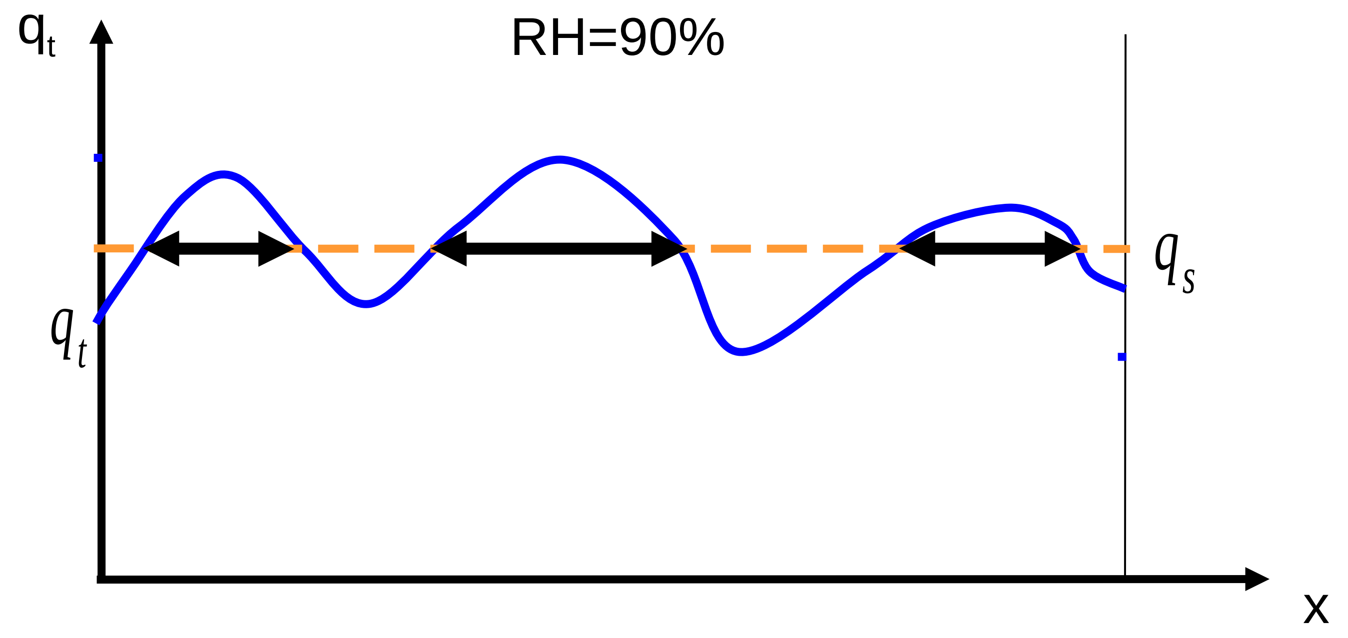
#1 Simple diagnostic schemes: RH-based schemes



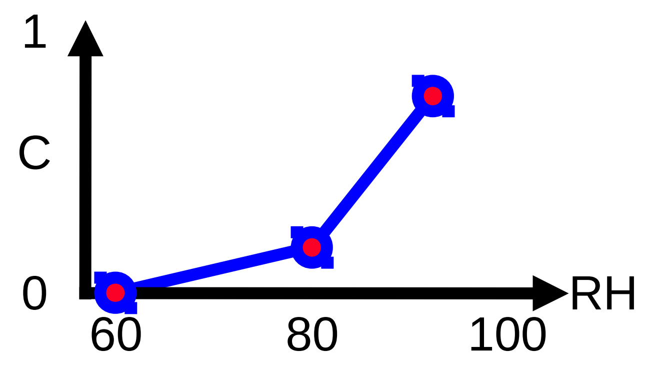
Add water vapour to the gridcell, the moistest part of the cell become saturated and cloud forms. The cloud cover is low.



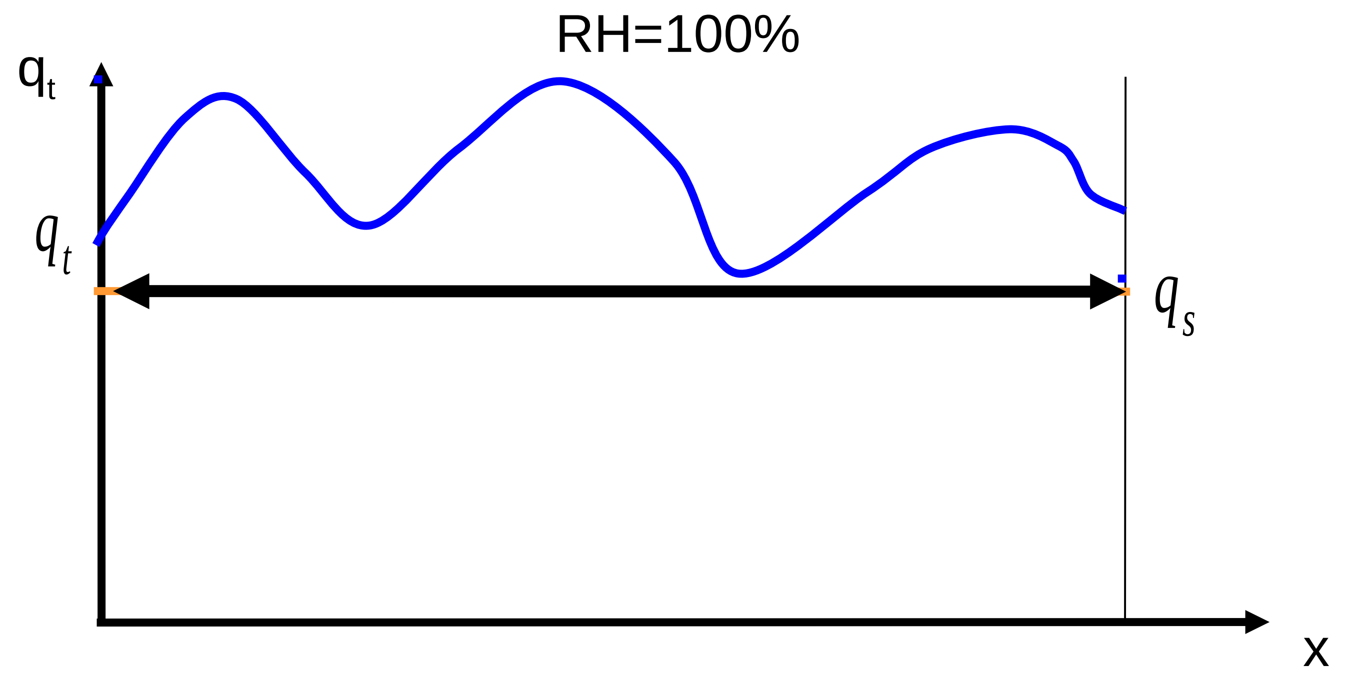
#1 Simple diagnostic schemes: RH-based schemes

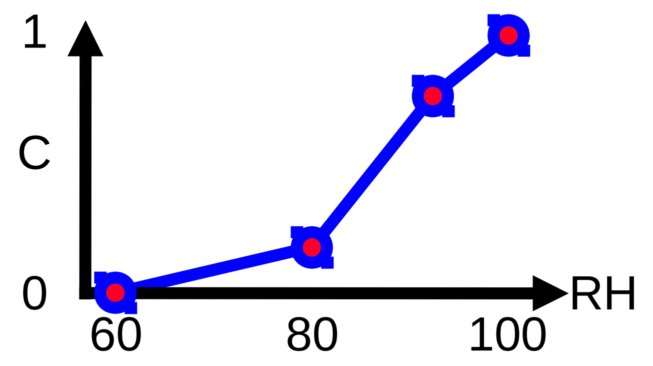


Further increases in RH increase the cloud cover



#1 Simple diagnostic schemes: RH-based schemes



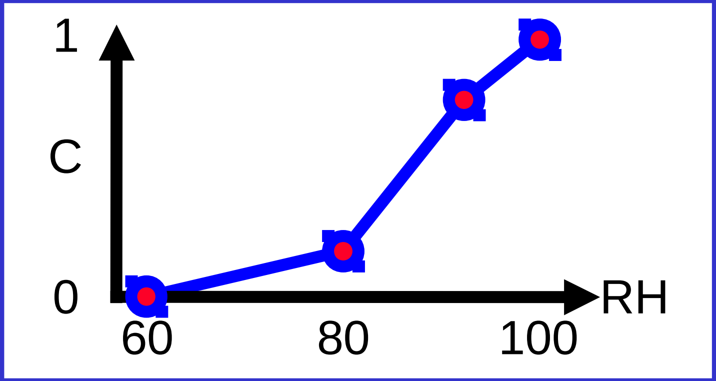


The grid cell becomes overcast when RH=100%, due to lack of supersaturation

#1 Simple Diagnostic Schemes:

Relative Humidity Schemes

- Many schemes, from the 1970s onwards, based cloud cover on the relative humidity (RH)



- e.g. Sundqvist et al. MWR 1

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

RH_{crit} = critical relative humidity at which cloud assumed to form

(function of height, typical value is 60-80%)

Diagnostic Relative Humidity Schemes

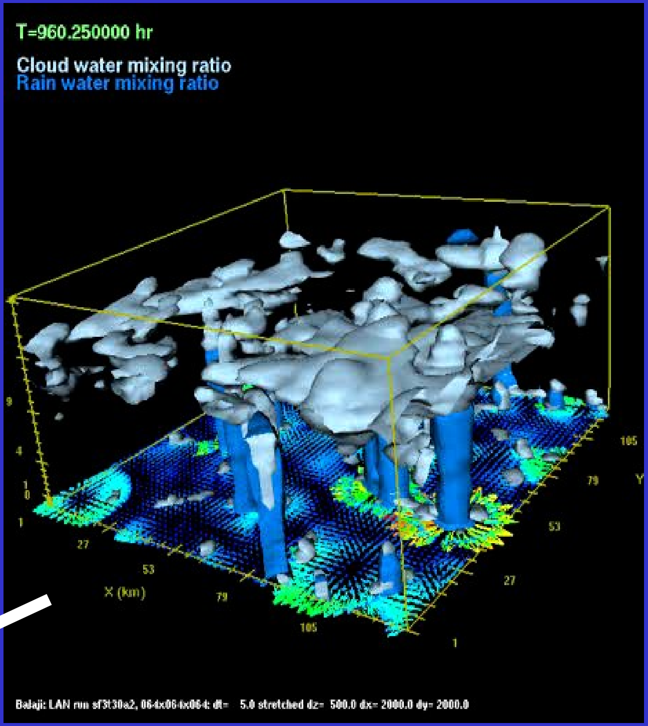
- Since these schemes form cloud when RH<100%, they implicitly assume subgrid-scale variability for total water, q_t, (and/or temperature, T) exists
- However, the actual PDF (the shape) for these quantities and their variance (width) are often not known
- *“Given a RH of X% in nature, the mean distribution of* q_t *is such that, on average, we expect a cloud cover of Y%”*

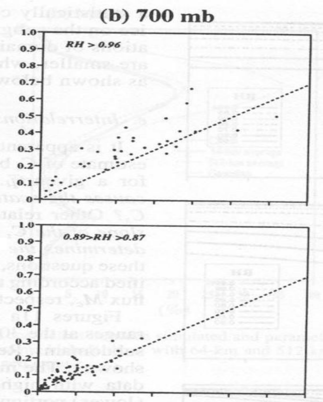
Diagnostic Relative Humidity Schemes

- 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:





$$C = F\left(RH, q_c\right)$$

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

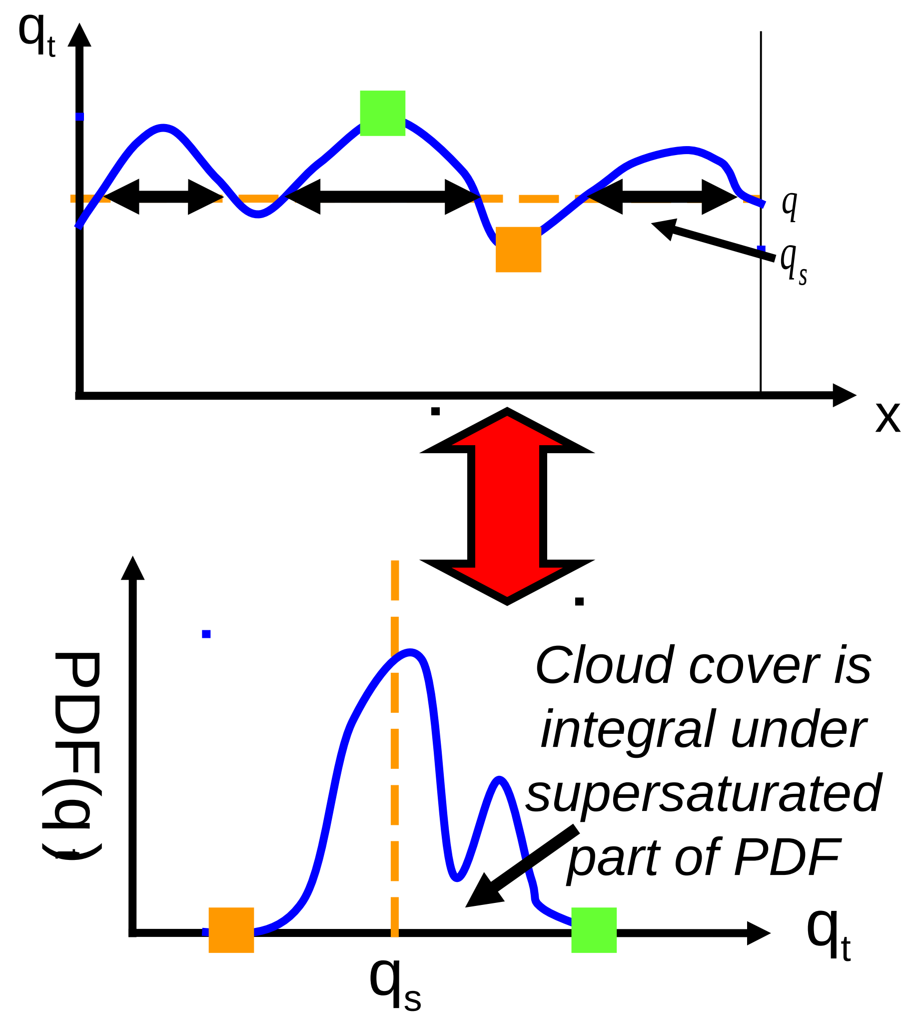
#2 Statistical Schemes

#2: Statistical Schemes

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

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

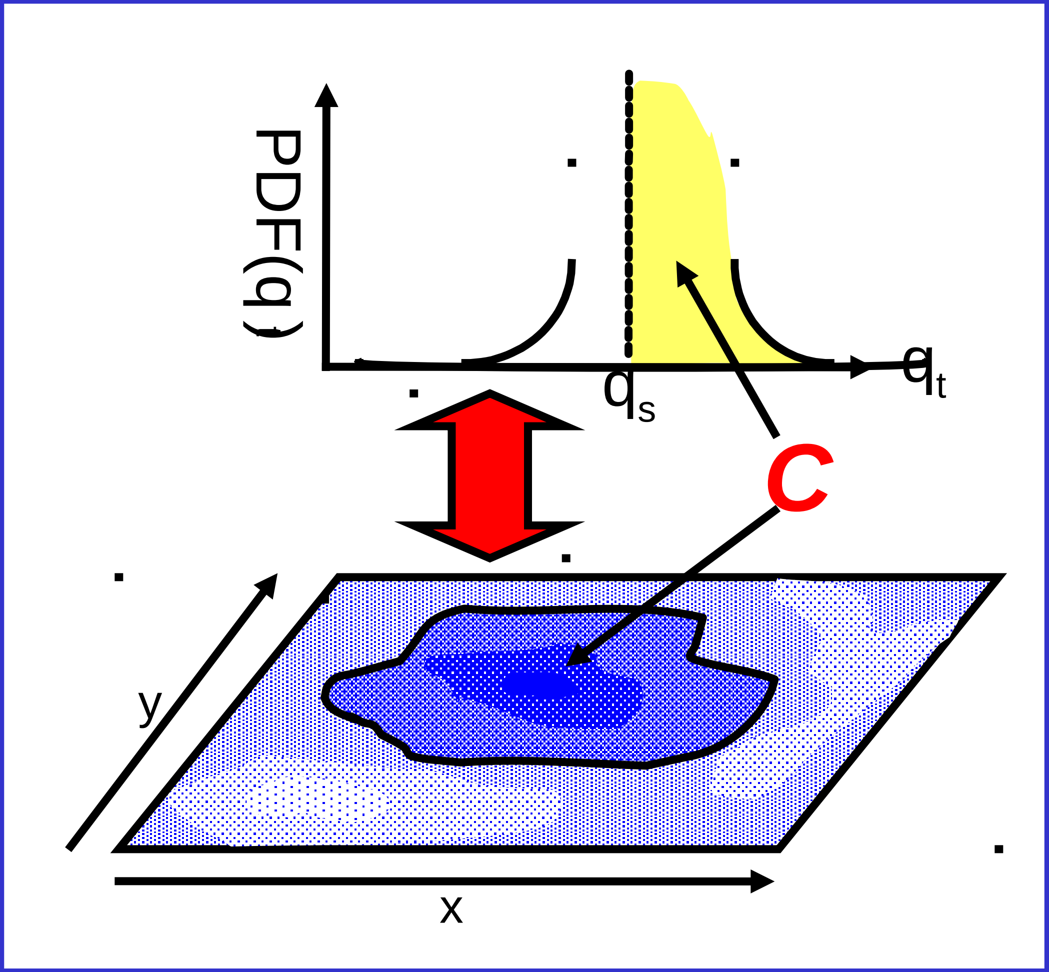
$$q_c = \int_{q_s}^{\infty} (q_t - q_s)\, PDF(q_t)\, dq_t$$



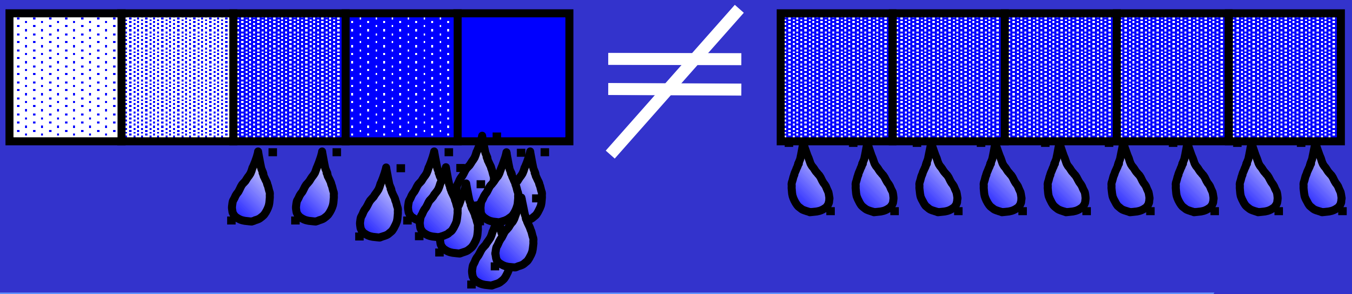
Cloud cover is integral under supersaturated part of PDF

#2: Statistical Schemes

- Knowing the PDF has advantages:
  - More accurate calculation of radiative fluxes
  - Unbiased calculation of microphysical processes
- However, location of clouds within gridcell unknown



e.g. microphysics bias



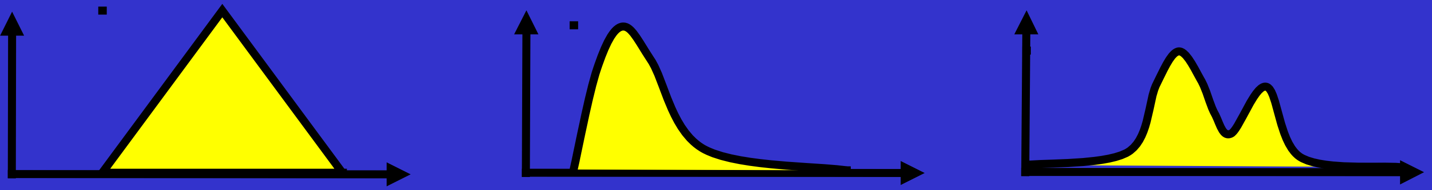
Statistical schemes

- Two tasks: Specification of the:

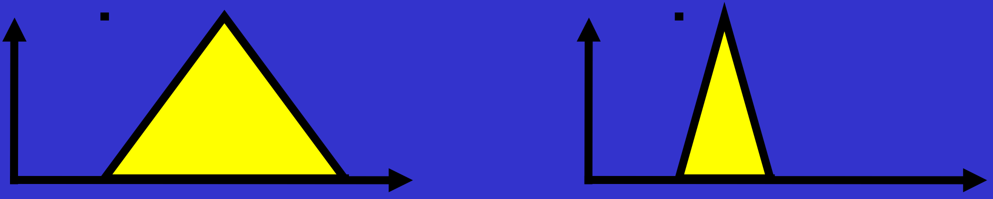
  (1) **PDF shape**

  (2) **PDF moments**

- Shape: Unimodal? bimodal? How many parameters?



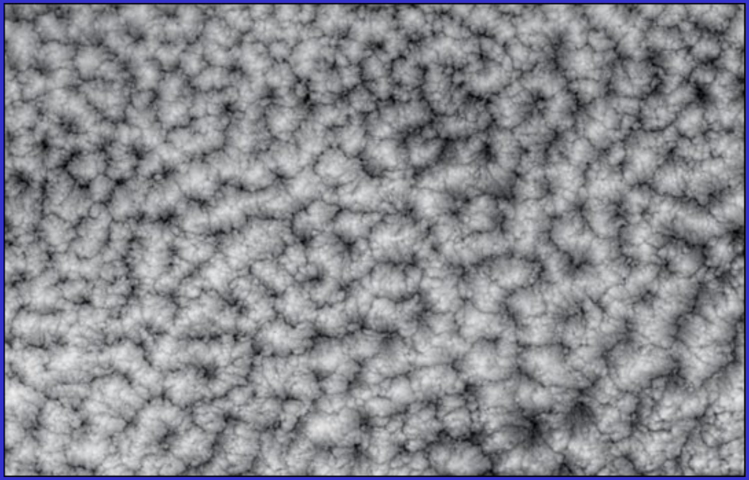
- Moments: How do we set those parameters?



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

modis image from NASA website



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

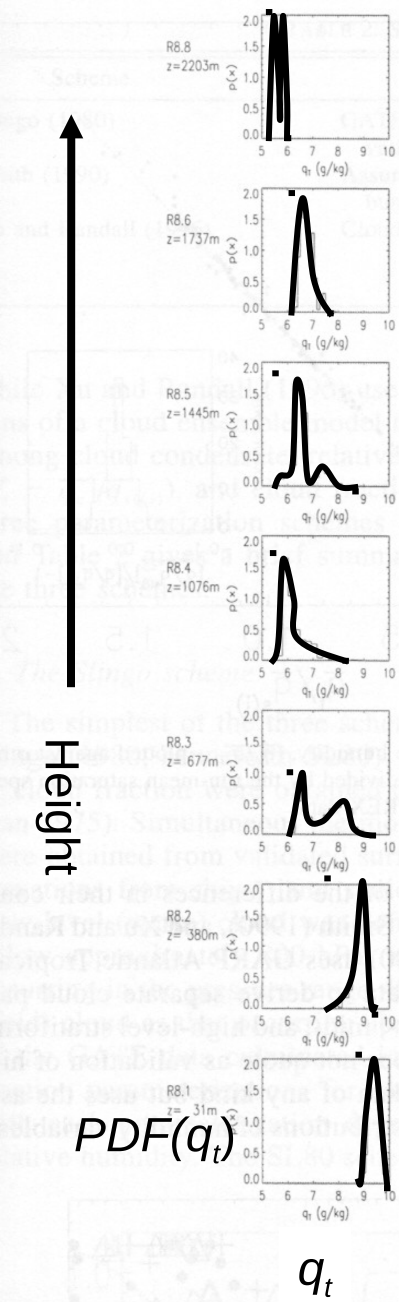


FIG. 2. Distributions of total water fr
penetrative cumulus during A

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

Aircraft Observed PDFs

Heymsfield and
McFarquhar
JAS 96
Aircraft IWC obs
during CEPEX

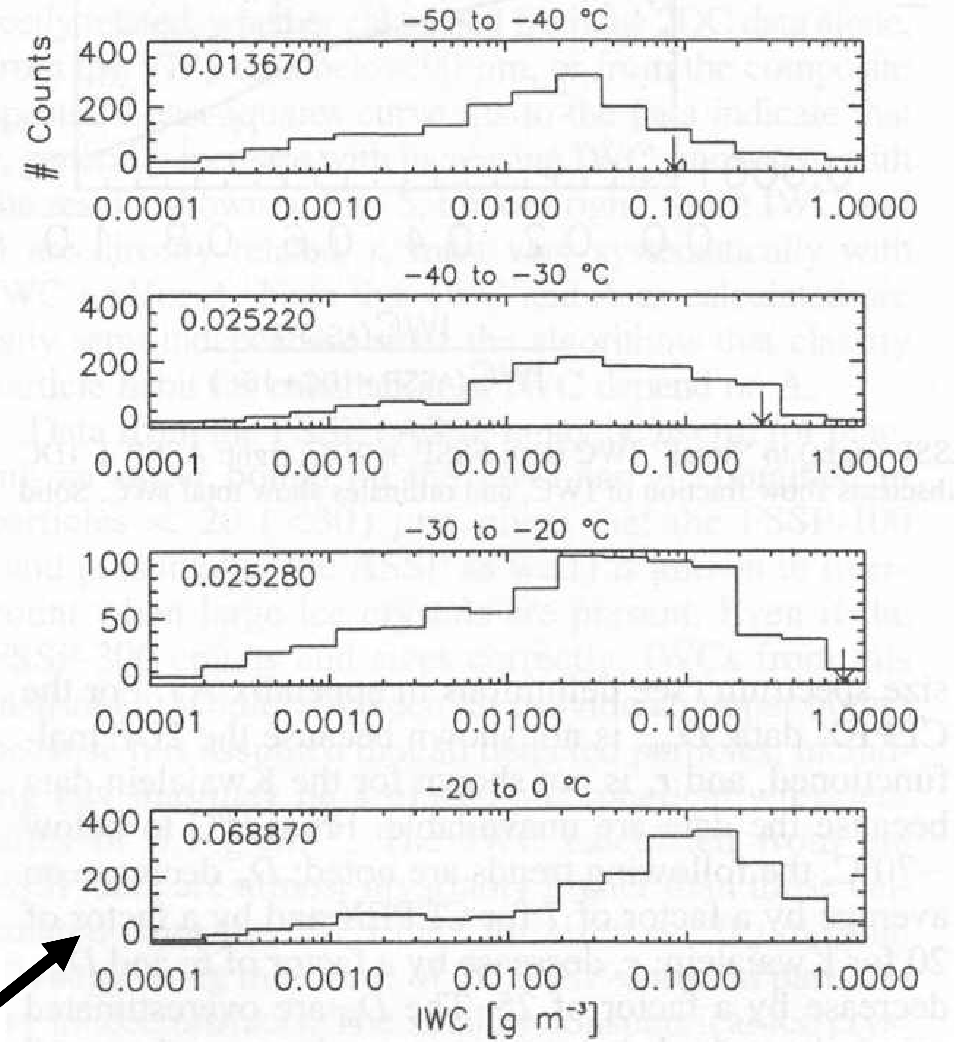


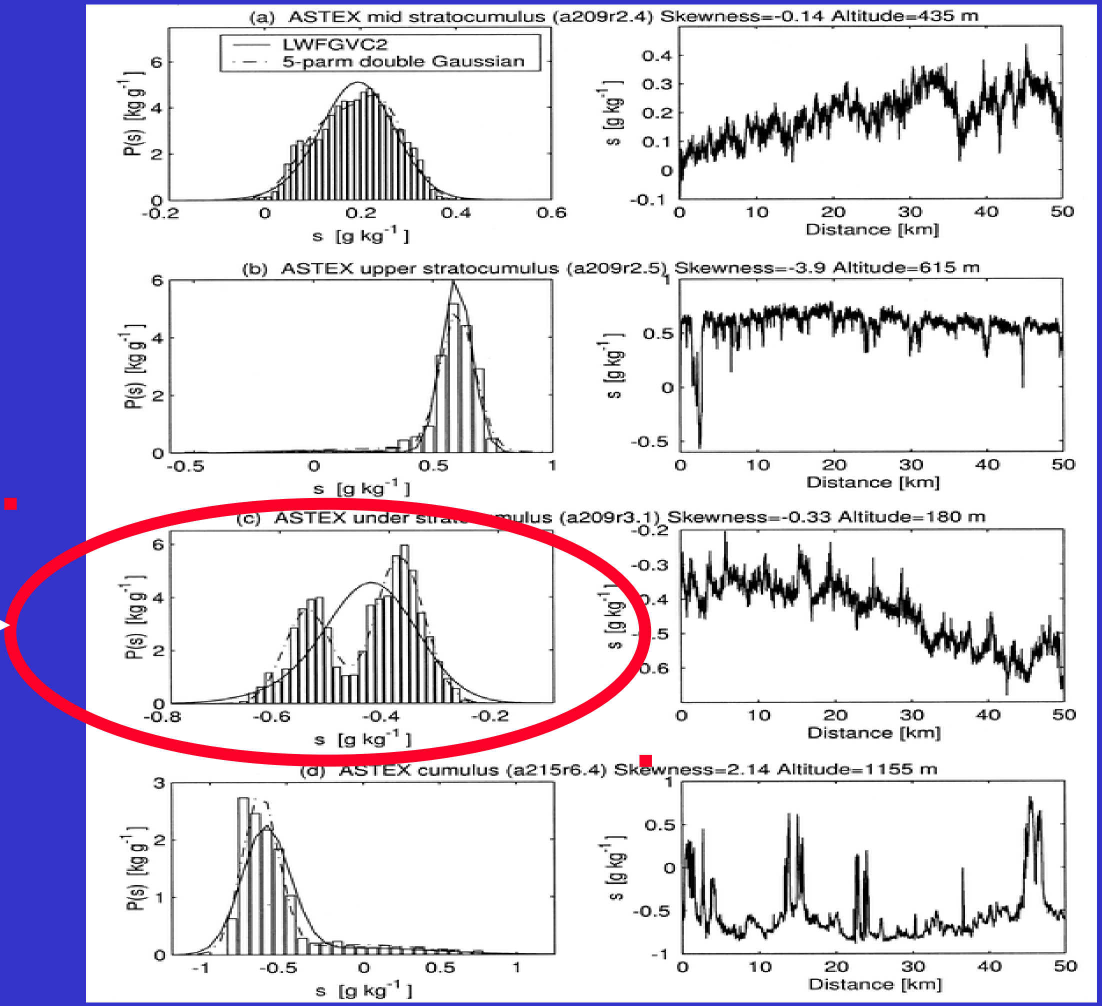
FIG. 9. Frequency distributions of IWC sorted by temperature from 2DC data during CEPEX. Each count (ordinate) represents 10-s average. Median IWC (g m^{-3}) in upper left corner of each panel. Arrows give saturation vapor density with respect to ice for midpoint of each temperature interval.

More examples from Larson et al. JAS 01/02

Note significant error that can occur if PDF is unimodal

PDF

Data

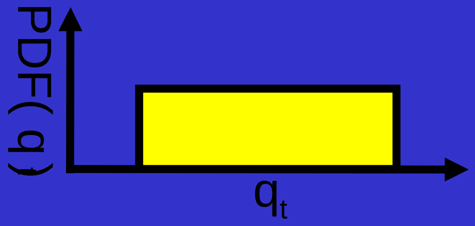


Conclusion: PDFs are mostly approximated by uni or bi-modal distributions, describable by a few parameters

TASK 1: Specification of PDF

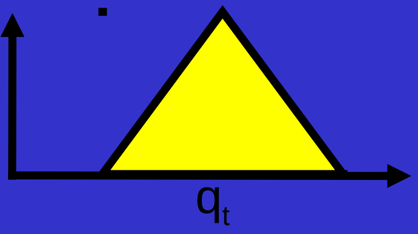
Many function forms have been used

symmetrical distributions:



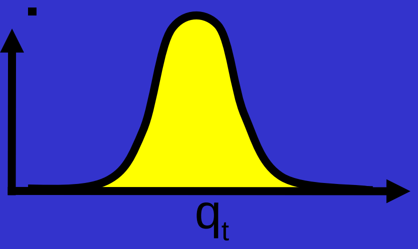
Uniform:

Letreut and Li (91)



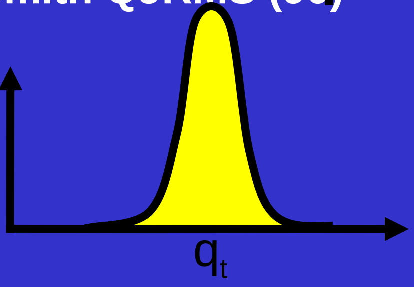
Triangular:

Smith QJRMS (90)



Gaussian:

Mellor JAS (77)

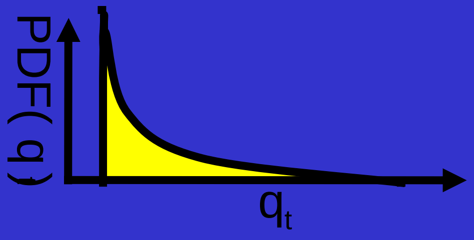


s^4 polynomial:

Lohmann et al. J. Clim (99)

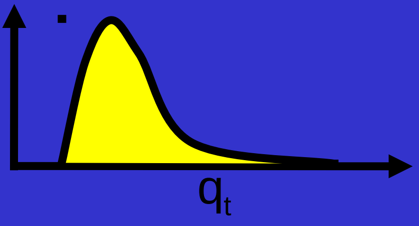
TASK 1: Specification of PDF

skewed distributions:



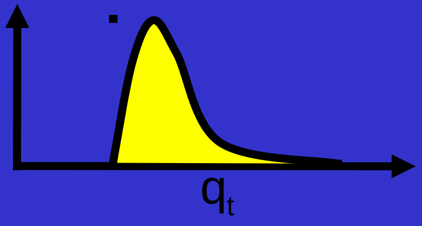
Exponential:

Sommeria and Deardorff JAS (77)



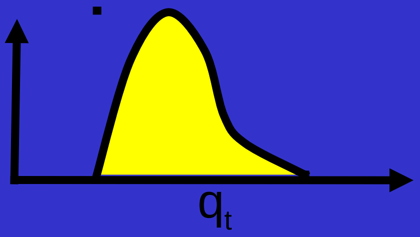
Lognormal:

Bony & Emanuel JAS (01)



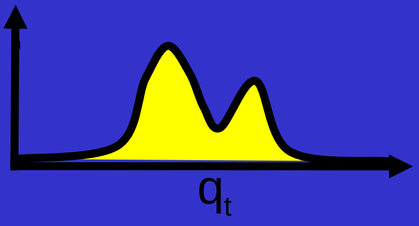
Gamma:

Barker et al. JAS (96)



Beta:

Tompkins JAS (02)

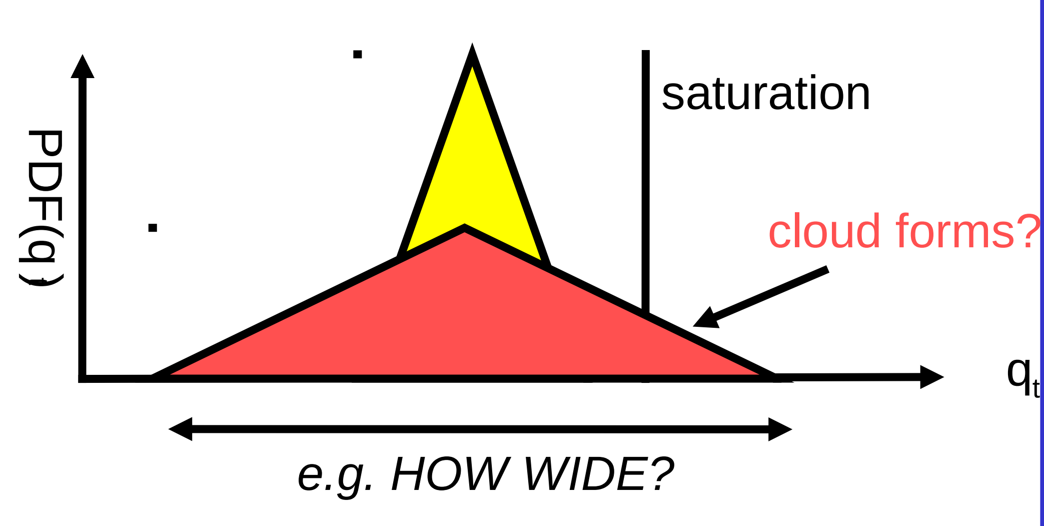


Double Normal/Gaussian:

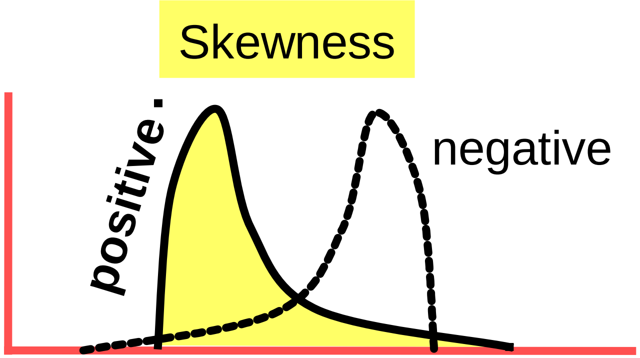
Lewellen and Yoh JAS (93), Golaz et al. JAS 2002

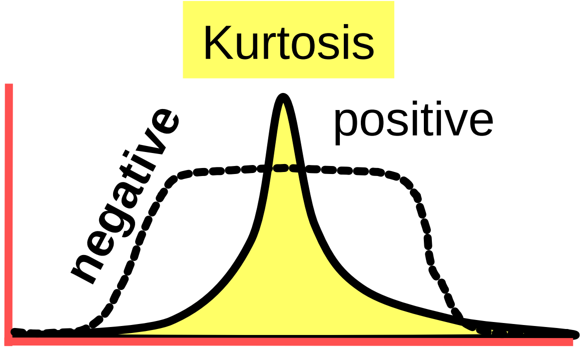
TASK 2: Specification of PDF moments

- Need also to determine the moments of the distribution:
  - Variance (Symmetrical PDFs)
  - Skewness (Higher order PDFs)
  - Kurtosis (4-parameter PDFs)



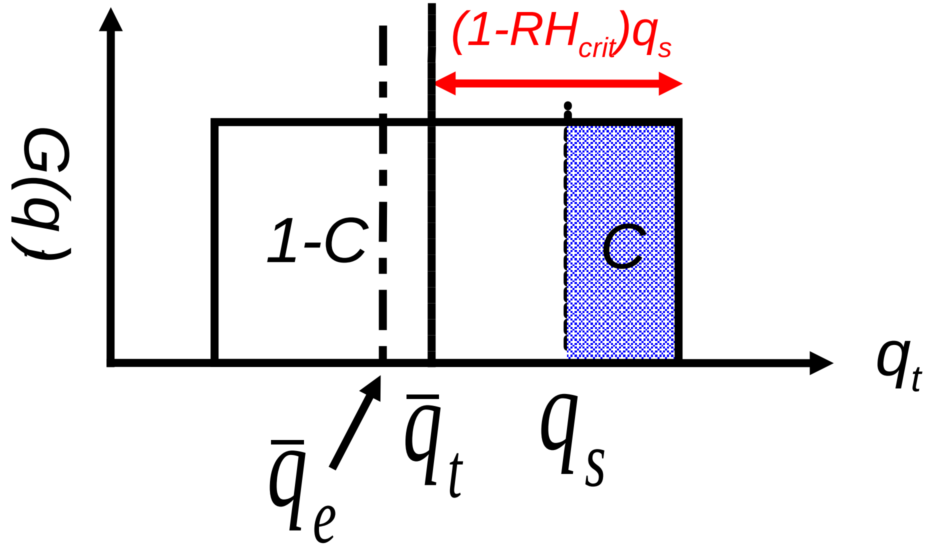
Moment 1=MEAN
Moment 2=VARIANCE
Moment 3=SKEWNESS
Moment 4=KURTOSIS





TASK 2: Specification of PDF moments

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



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

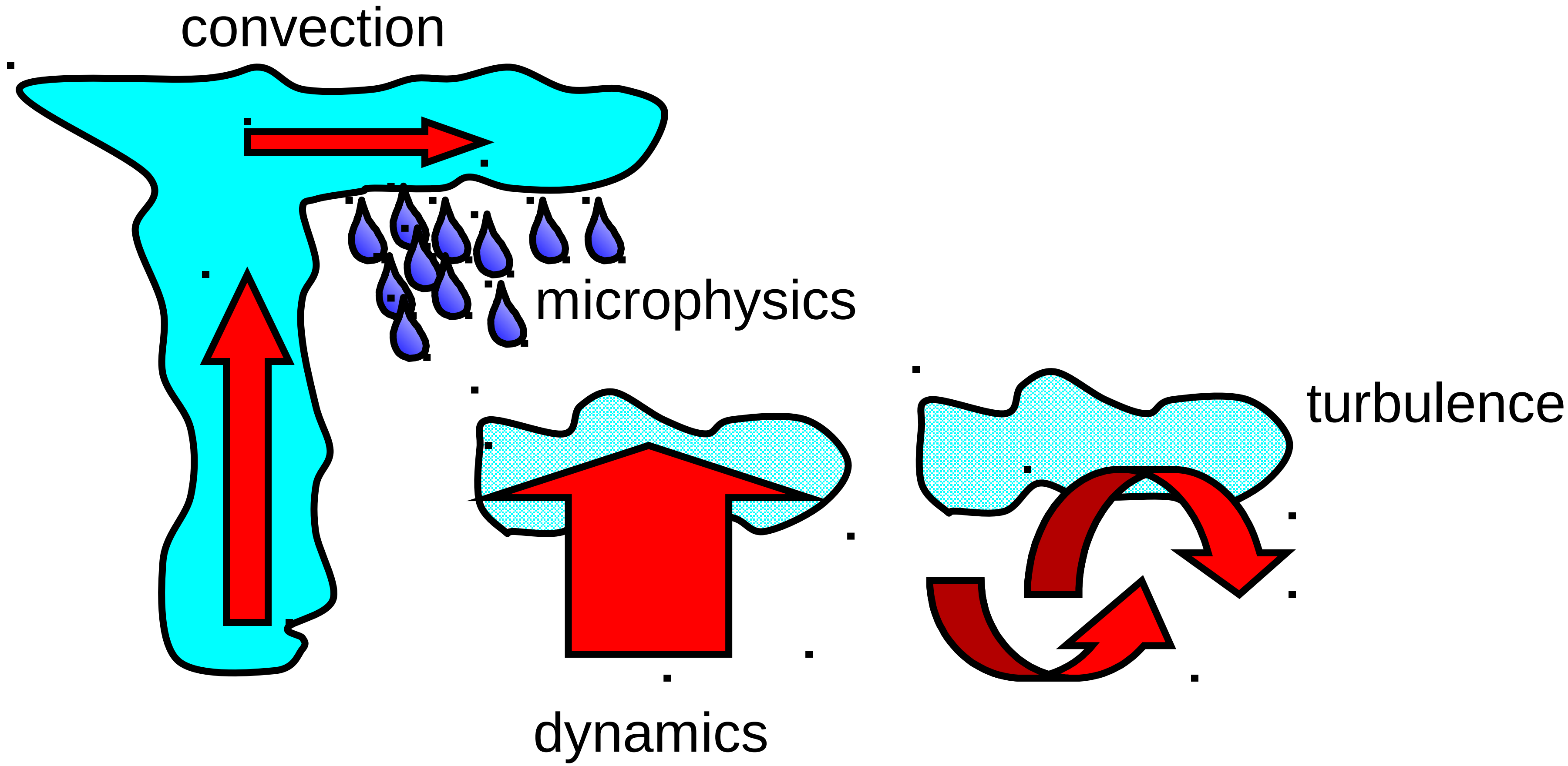
where $$\bar{q}_e = q_s\left(1-(1-RH_{crit})(1-C)\right)$$

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

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

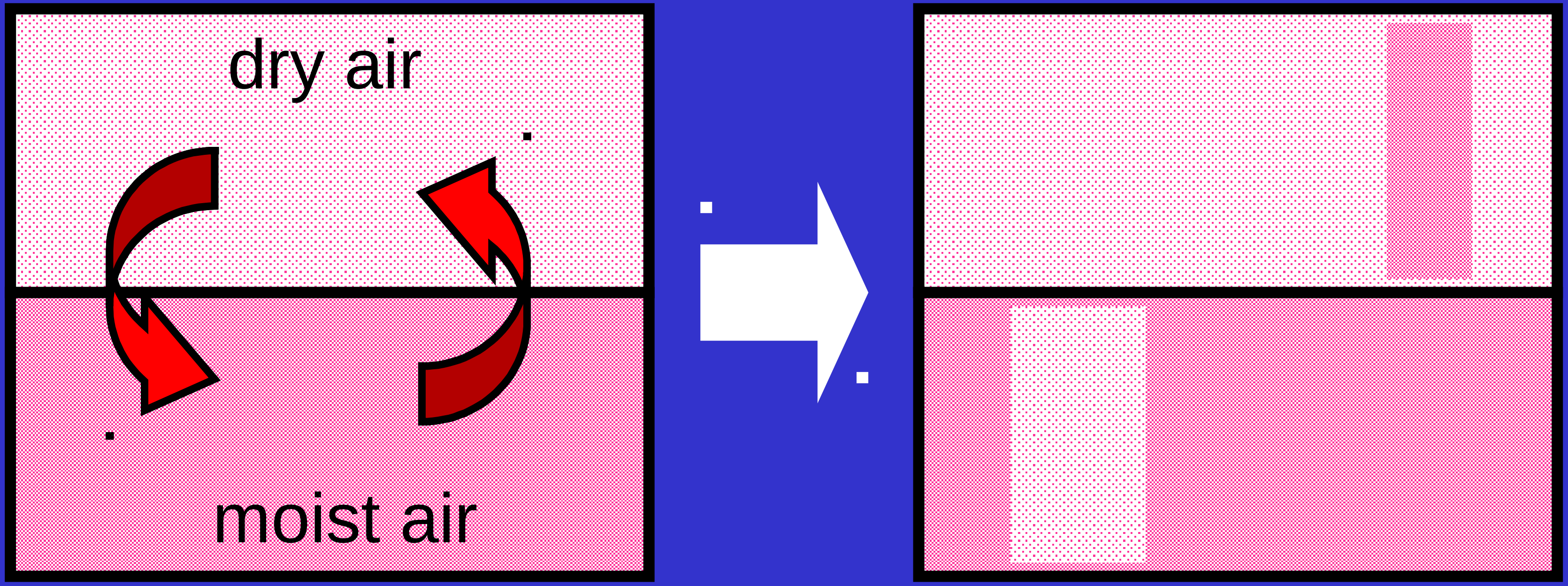
Sundqvist formulation!!!

Clouds in GCMs
Processes that can affect distribution moments



Example: Turbulence

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



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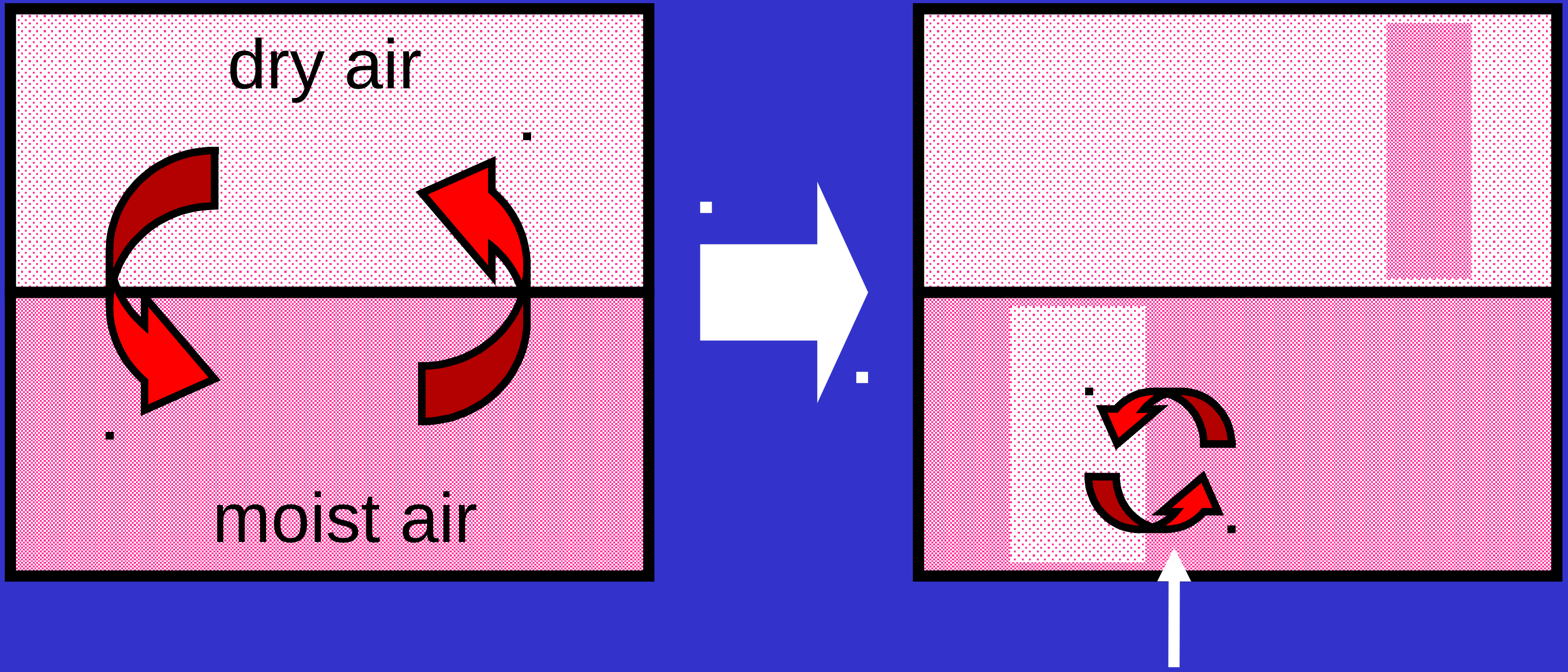
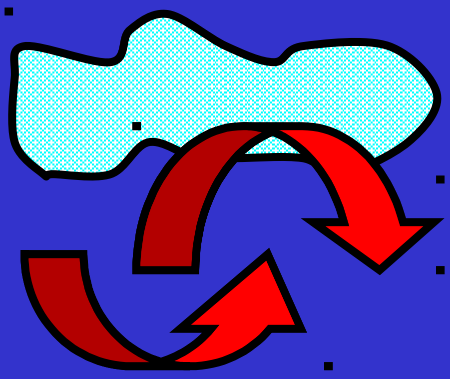


while mixing in the horizontal plane naturally reduces the horizontal variability

Specification of PDF moments

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



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

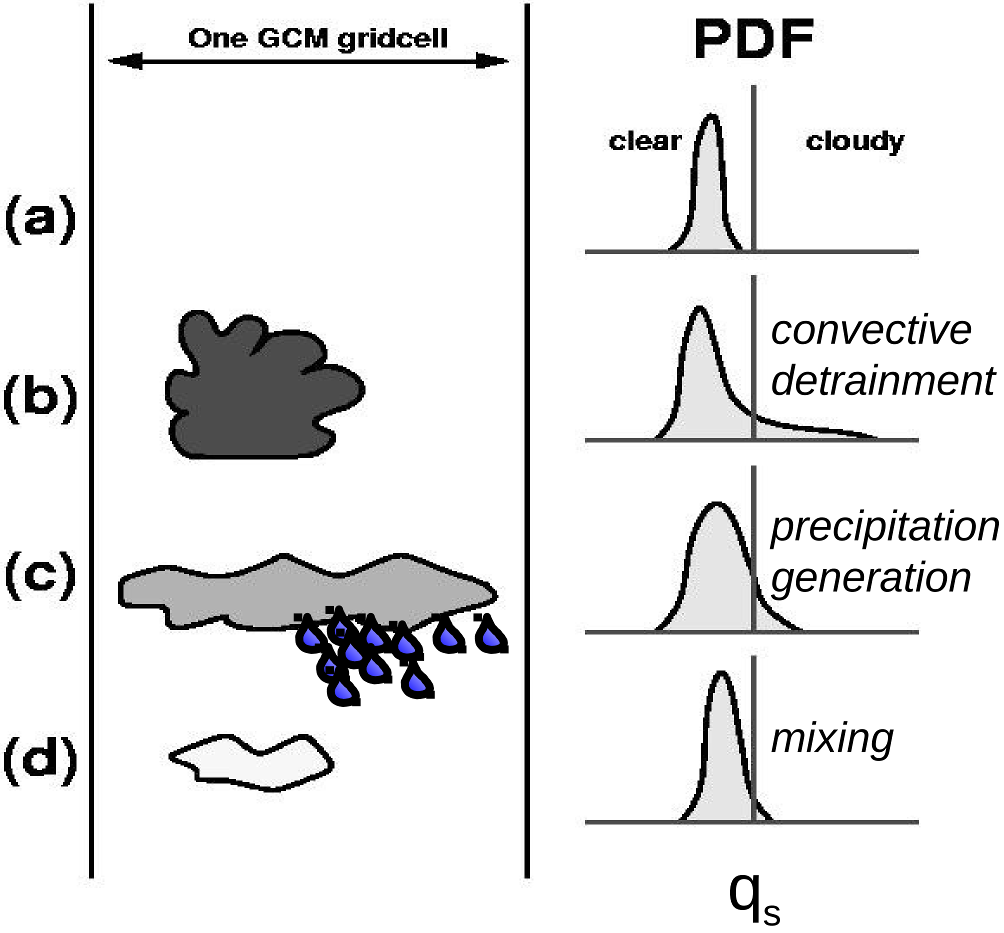
Source dissipation

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

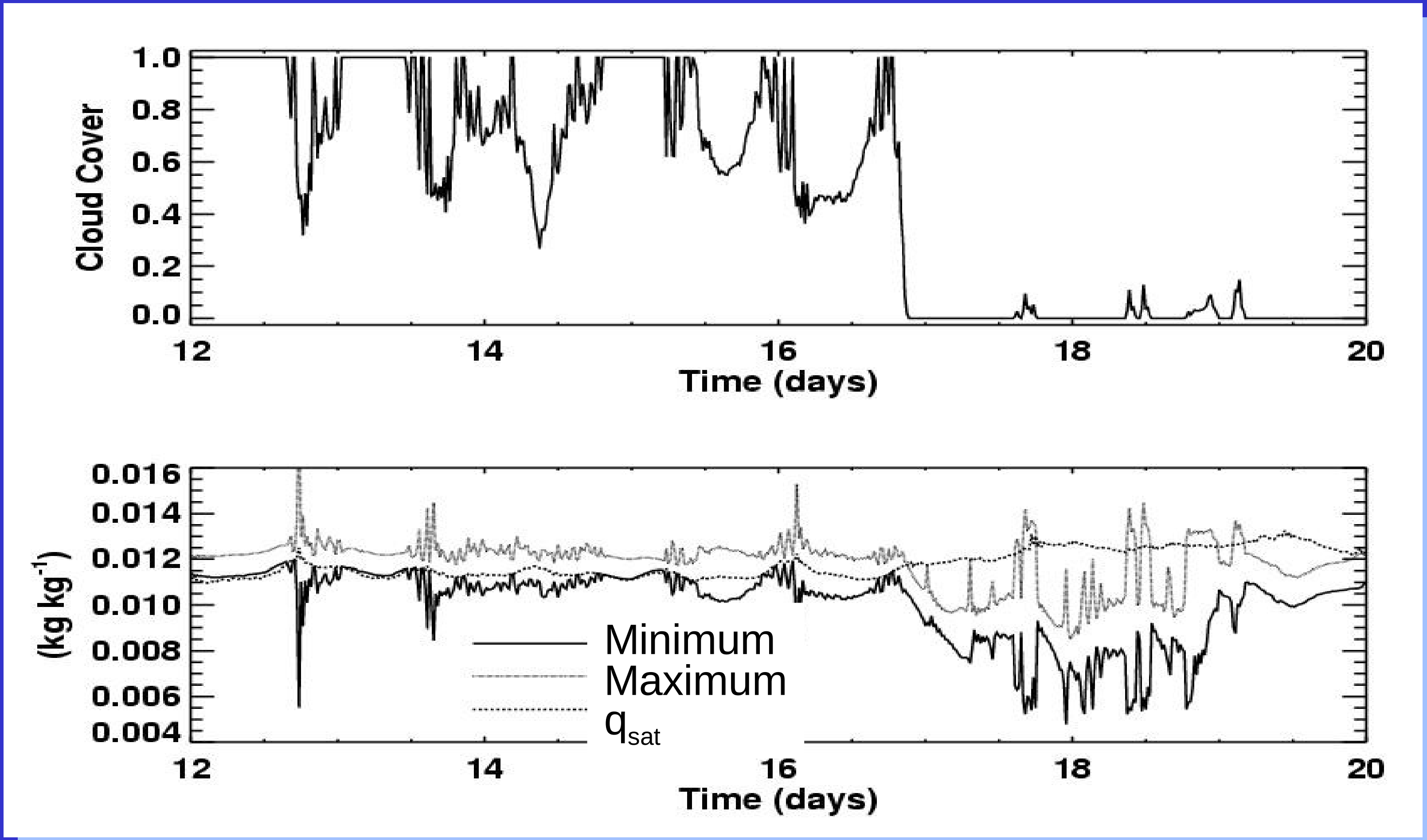
- Disadvantage:
  - Can give good estimate in boundary layer, but above, other processes will determine variability, that evolve on slower timescales

Prognostic Statistical Scheme

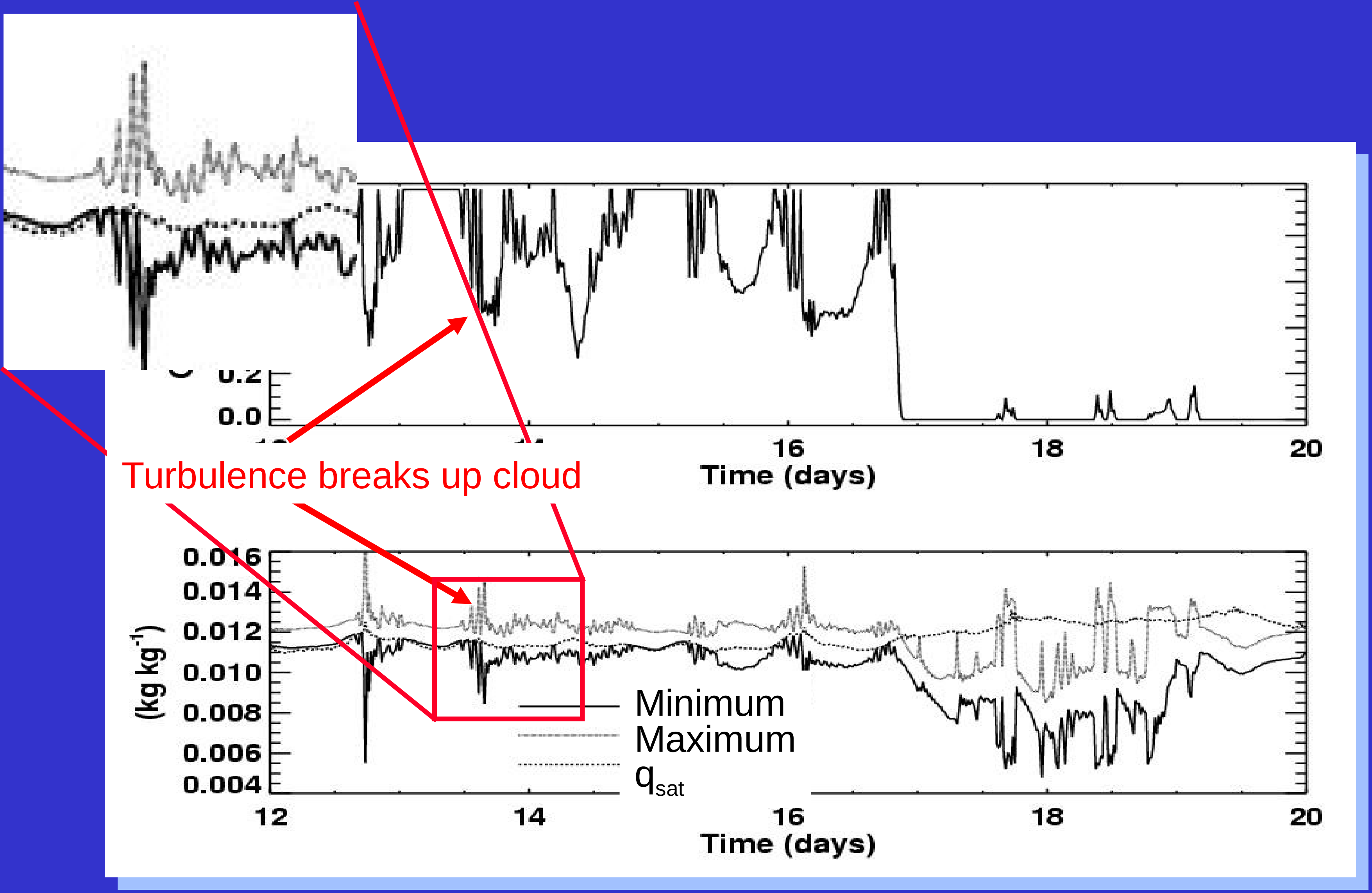
- Tompkins (2002) introduced a prognostic statistical scheme into ECHAM5 climate GCM
- Prognostic equations are introduced for the variance and skewness of the total water PDF
- Some of the sources and sinks are rather ad-hoc in their derivation!



Scheme in action

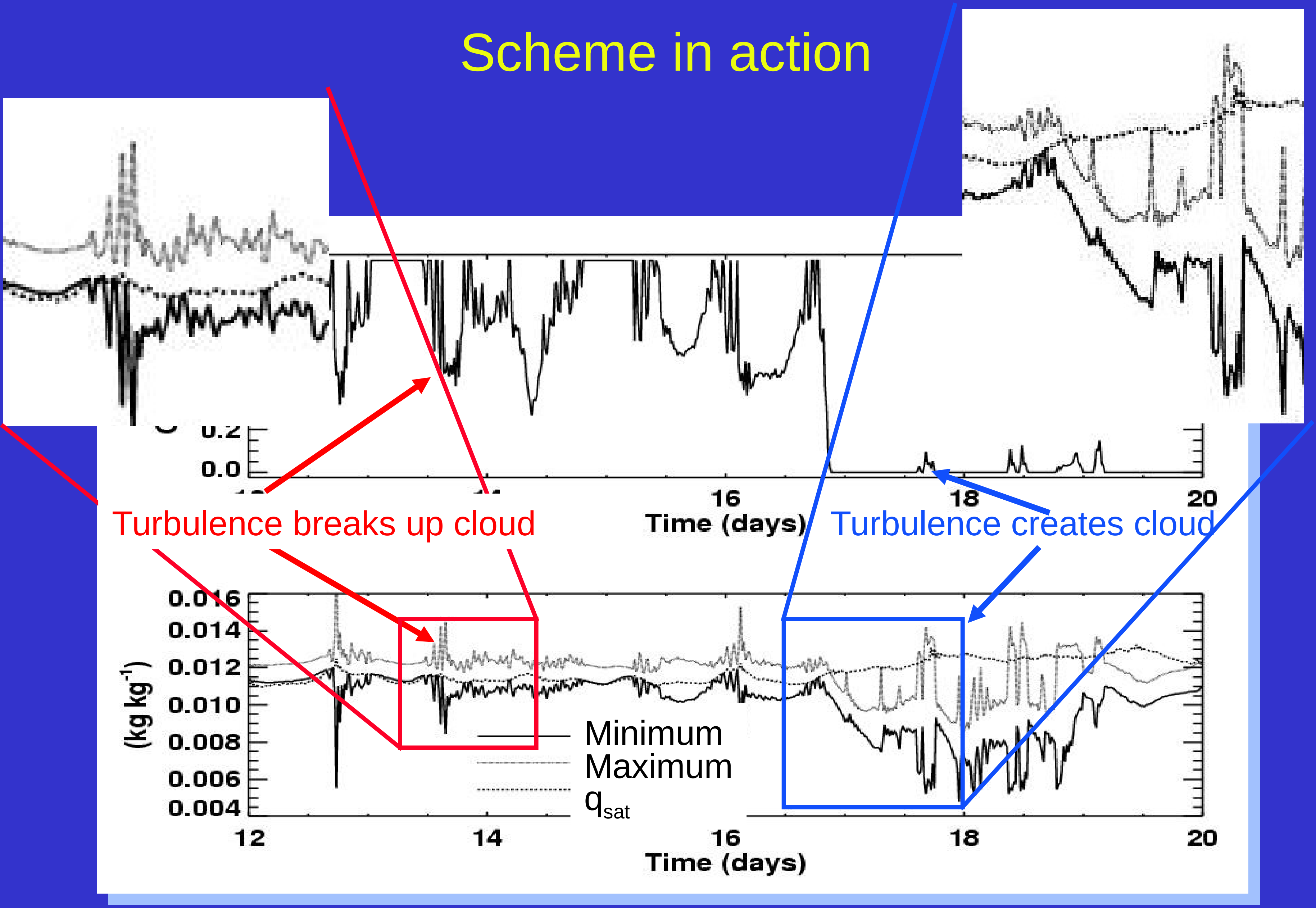


Scheme in action



Turbulence breaks up cloud

Scheme in action



Turbulence breaks up cloud

Turbulence creates cloud

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 self-consistent
- Disadvantages
  - Deriving these sources and sinks rigorously is hard, especially for higher order moments needed for more complex PDFs!
  - If variance and skewness are used instead of cloud water and humidity, conservation of the latter is not ensured

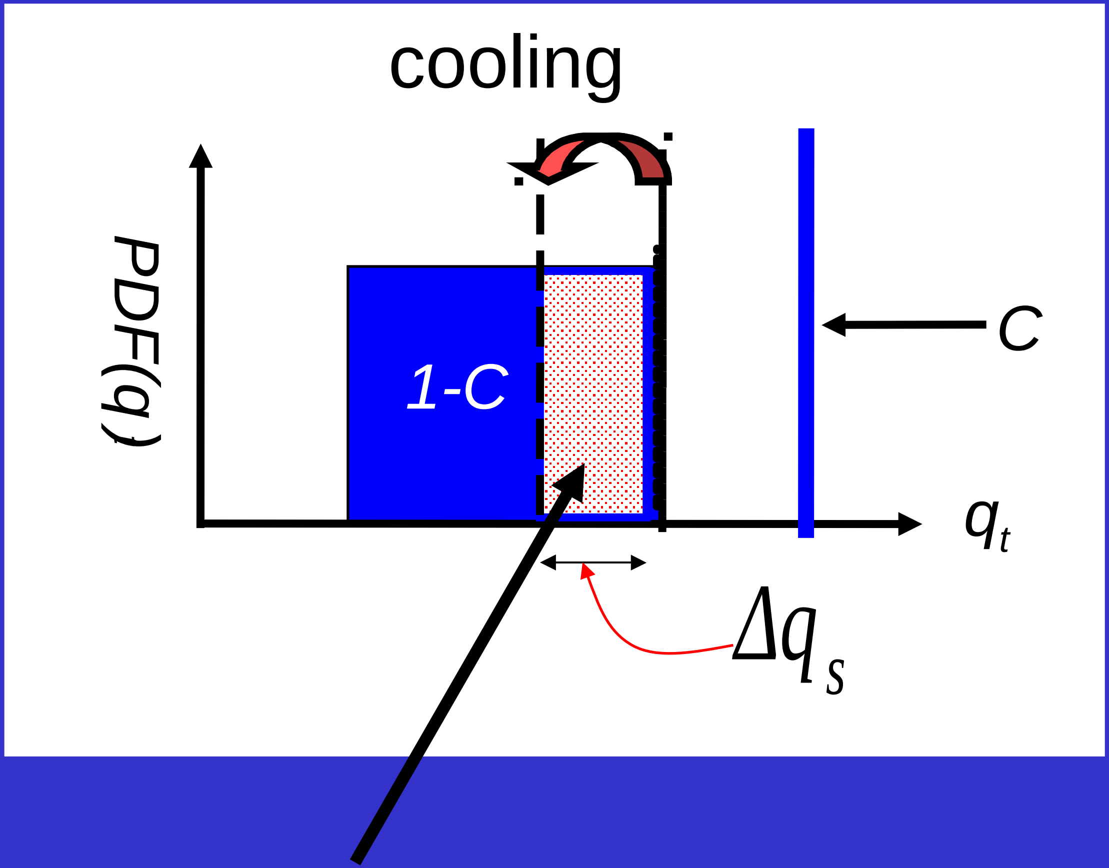
#3 The ECMWF scheme

ECMWF Scheme

Tiedtke MWR 1993

- The ECMWF cloud scheme introduces two prognostic equations for cloud water and cloud cover
- As for the prognostic statistical scheme, each process of convection, turbulence, microphysics and dynamics provides sources and sinks of these variables
- These terms are *often* derived assuming a subgrid-scale distribution of total water
- Effectively a “variable transformation”

Example: (a)diabatic heating/cooling



ECMWF PDF is (mostly)

Uniform: in clear sky part

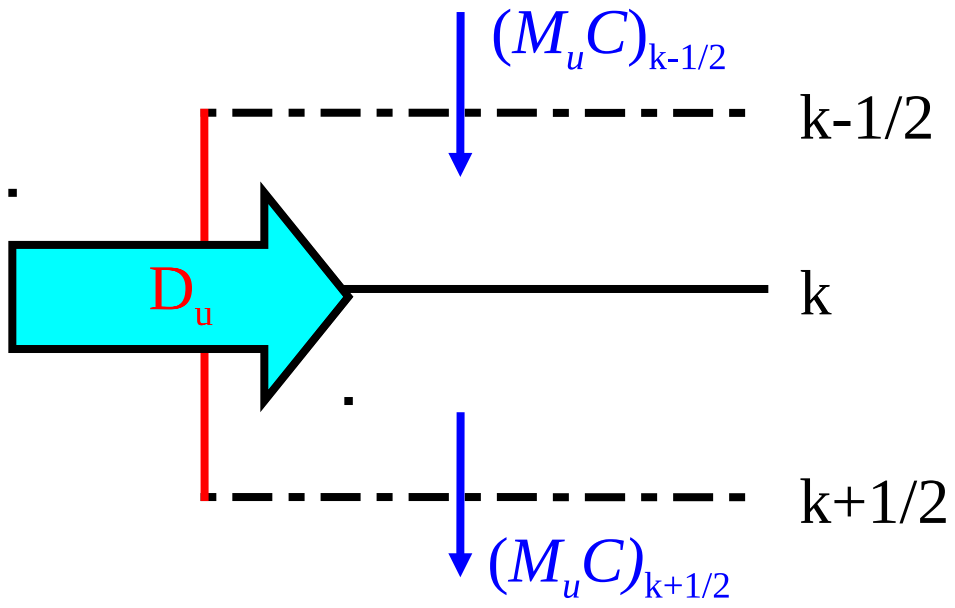
Delta: in cloudy part

Red-hashed area is the change in cloud fraction due to cooling, this is added to the cloud cover budget

Advantages

- Some terms are easier to handle with a simple cloud cover variable
- e.g. Convective detrainment:

$$S(C)_{CV} = \frac{D_u}{\rho}(1-C) + \frac{M_u}{\rho}\frac{\partial C}{\partial z}$$



Disadvantages

- Not all terms are derived using PDF assumptions, therefore easy for scheme to render unreasonable states.
  - Cloud water $q_c = 0$, Cloud cover $C > 0$ or vice versa
  - Cloud variables are like a celebrities…

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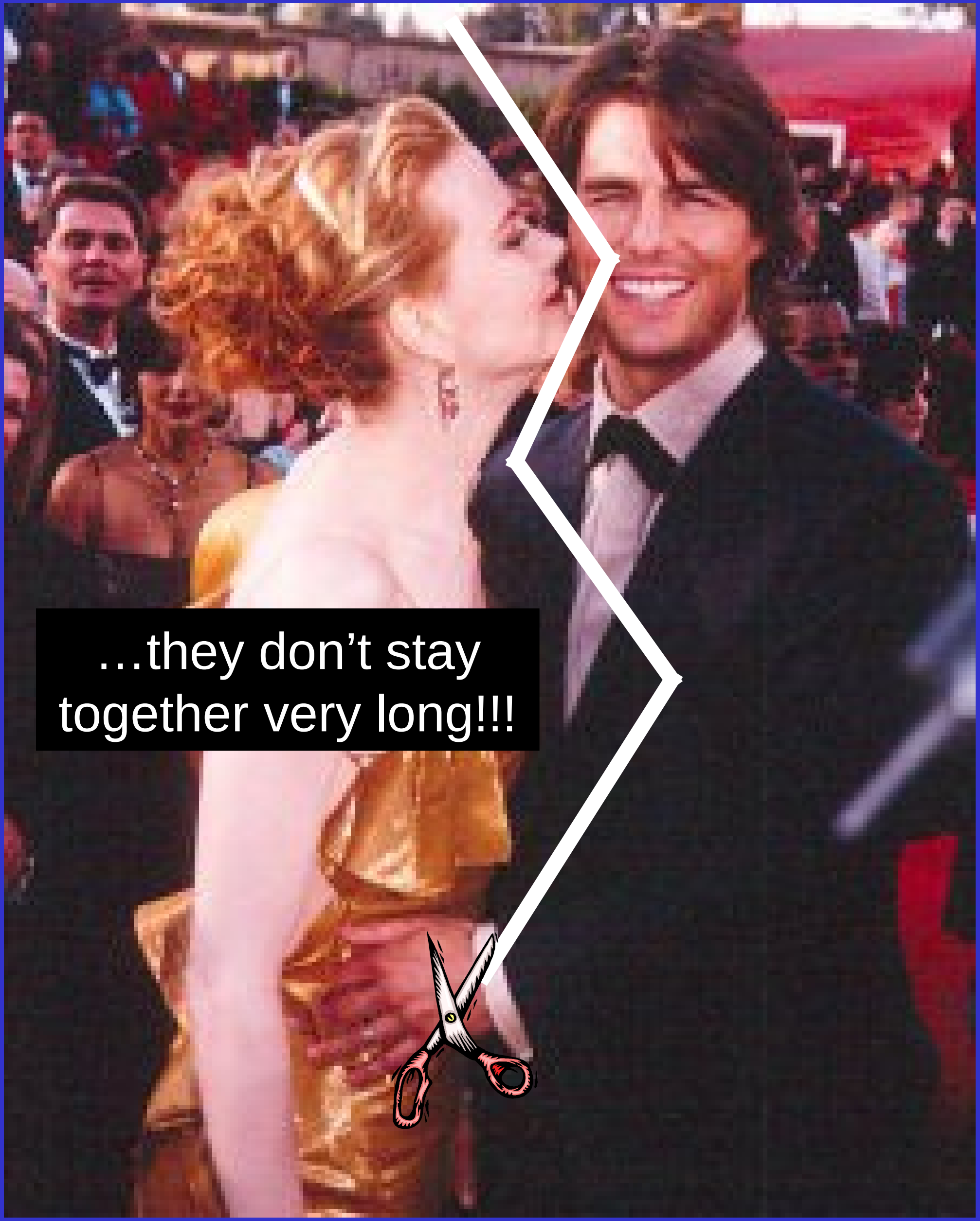
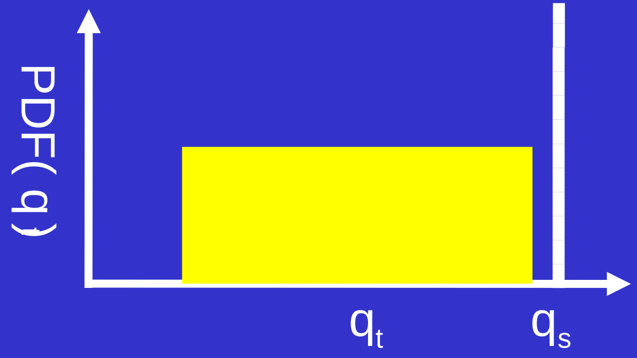


…they don’t stay together very long!!!

Disadvantages

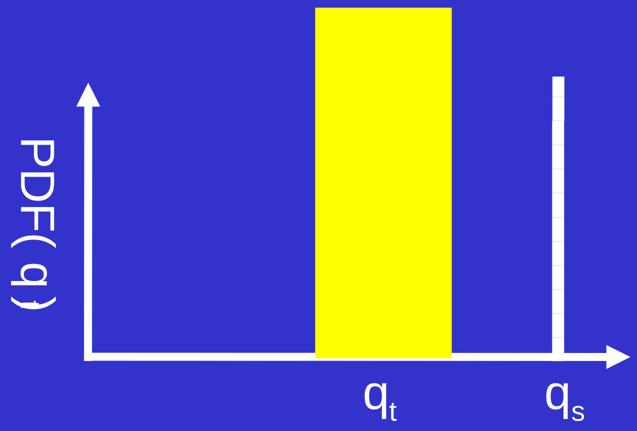
- Loss of “memory” in clear sky or overcast conditions; scheme is not “reversible”.
  - e.g: RH=80%, C=0, q_c=0

wide distribution?



Cloud would form with small cooling!

narrow distribution?
(clear long time?)



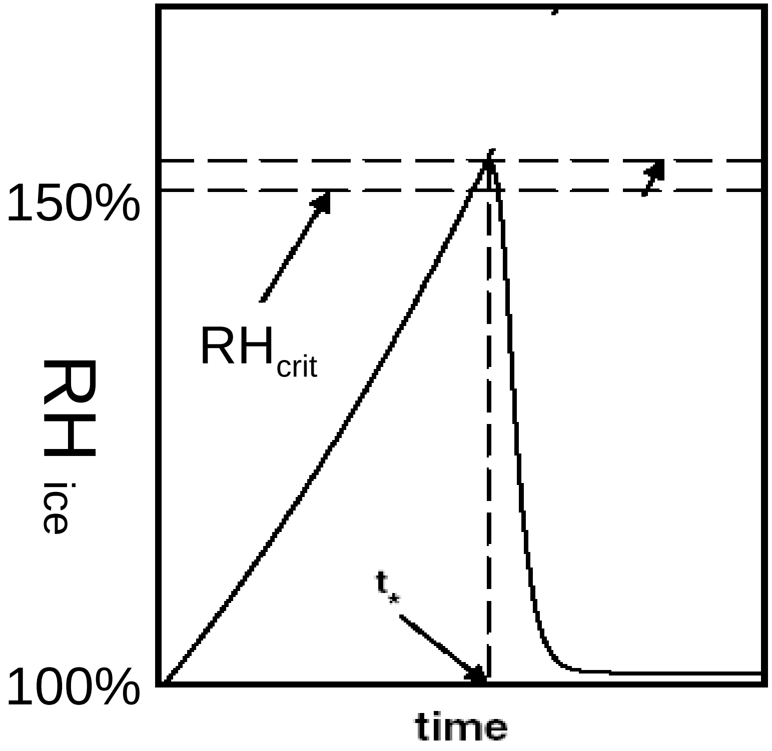
…but not in this case!

#4 Ice complications

Cirrus and permanent contrail cloud over my back garden, Reading, UK. Summer 2005.

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°C
- 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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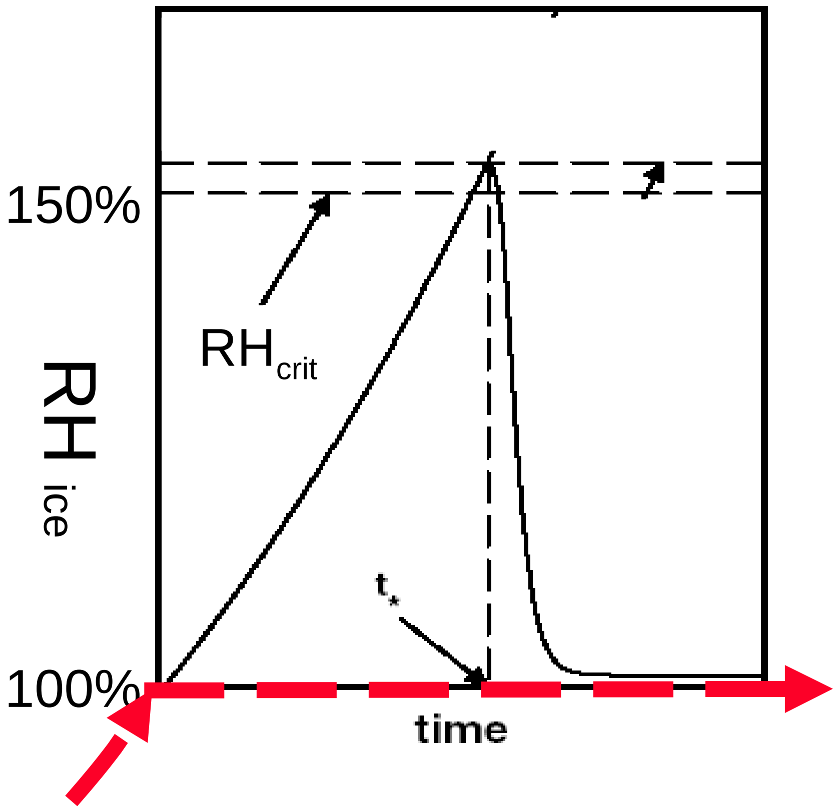

Typical GCM
No supersaturation

ECMWF current operations

Ice complications

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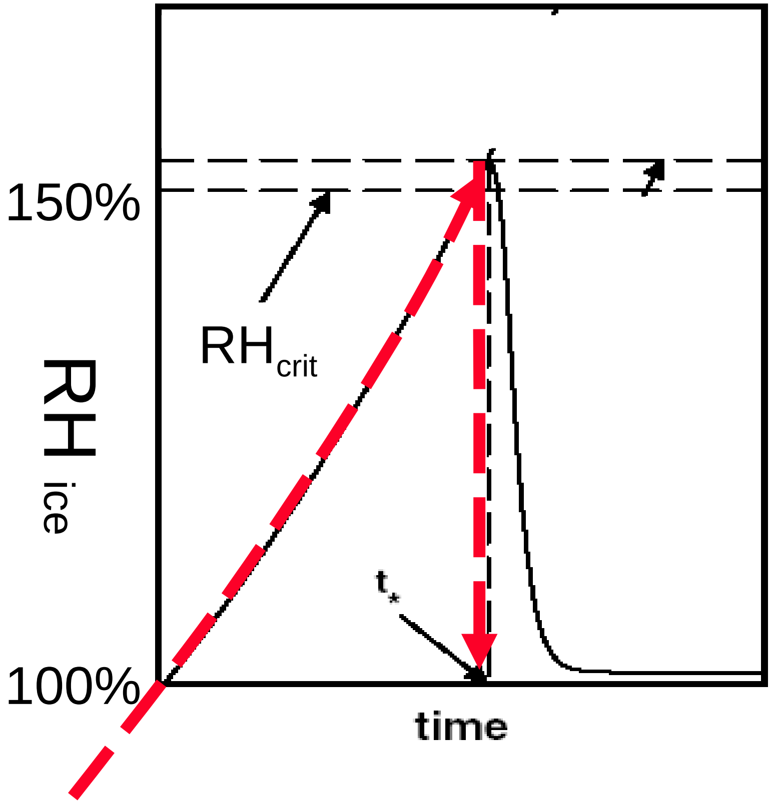
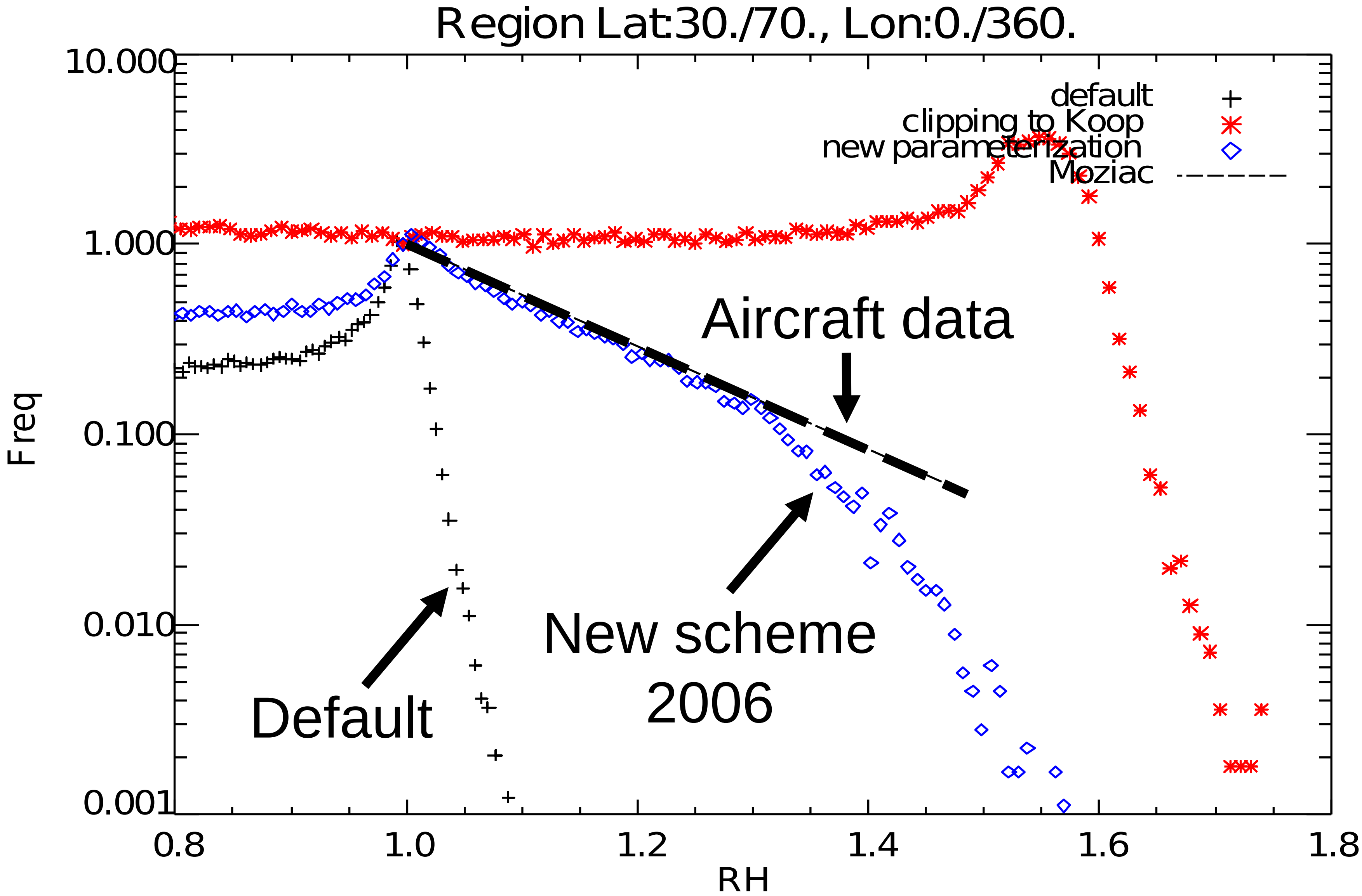


Threshold allowed
but no nucleation timescale

ECMWF 2006!!!

Simple ECMWF scheme: comparison to Mozaic aircraft data



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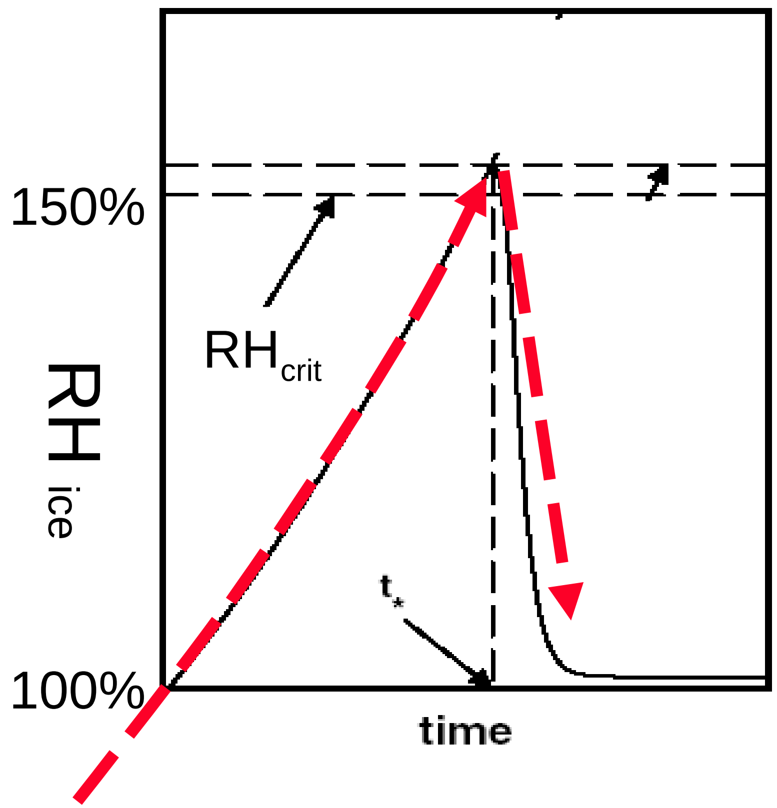
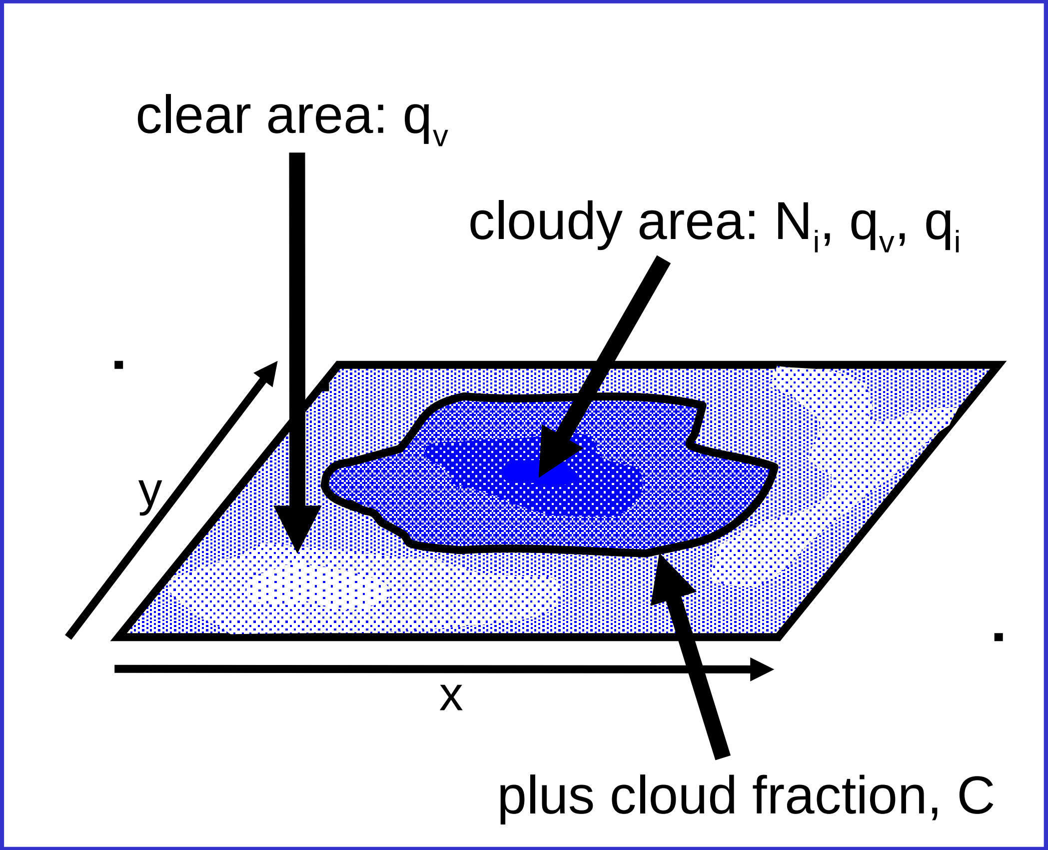


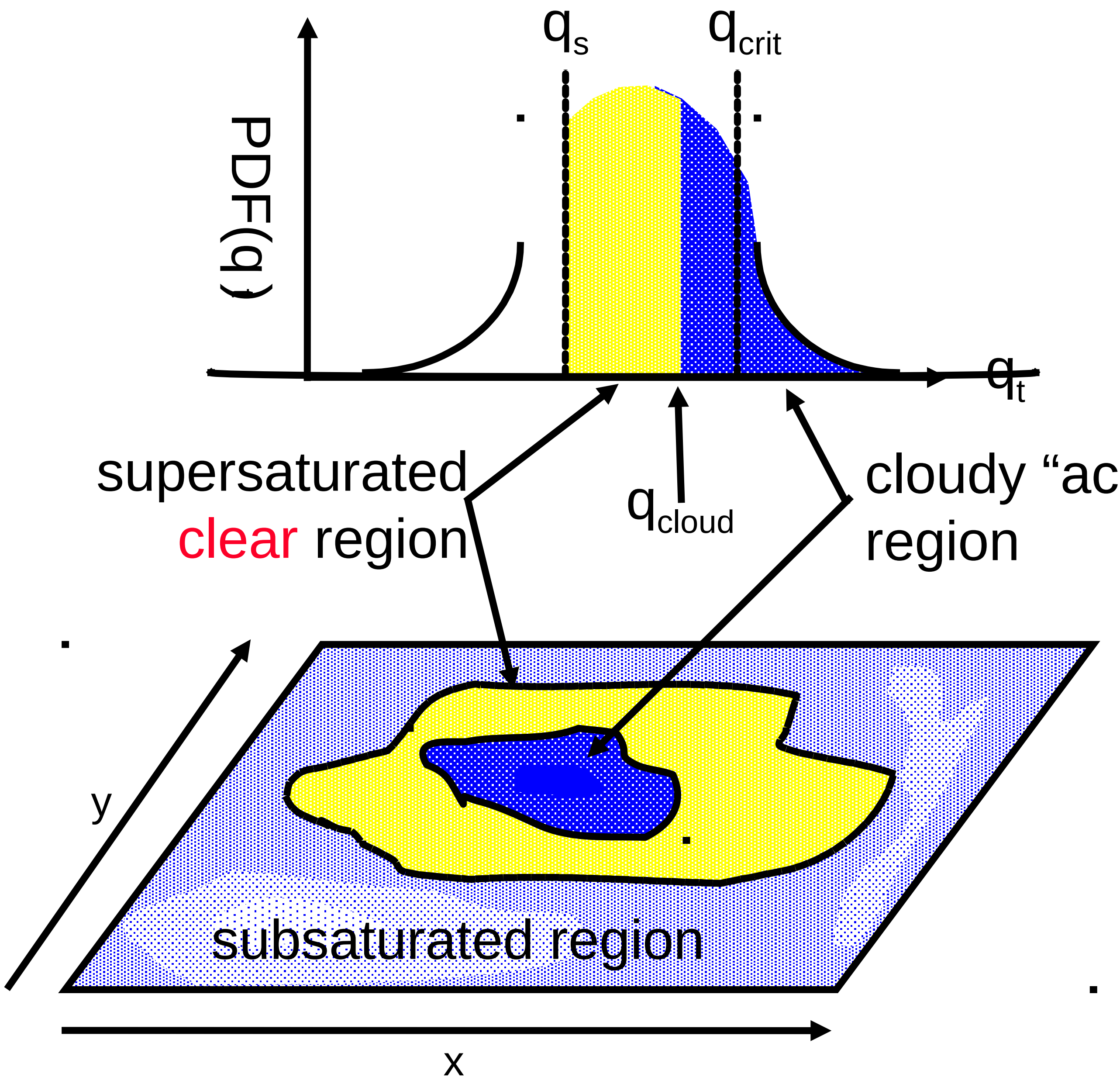
full scheme, nice
but requires…

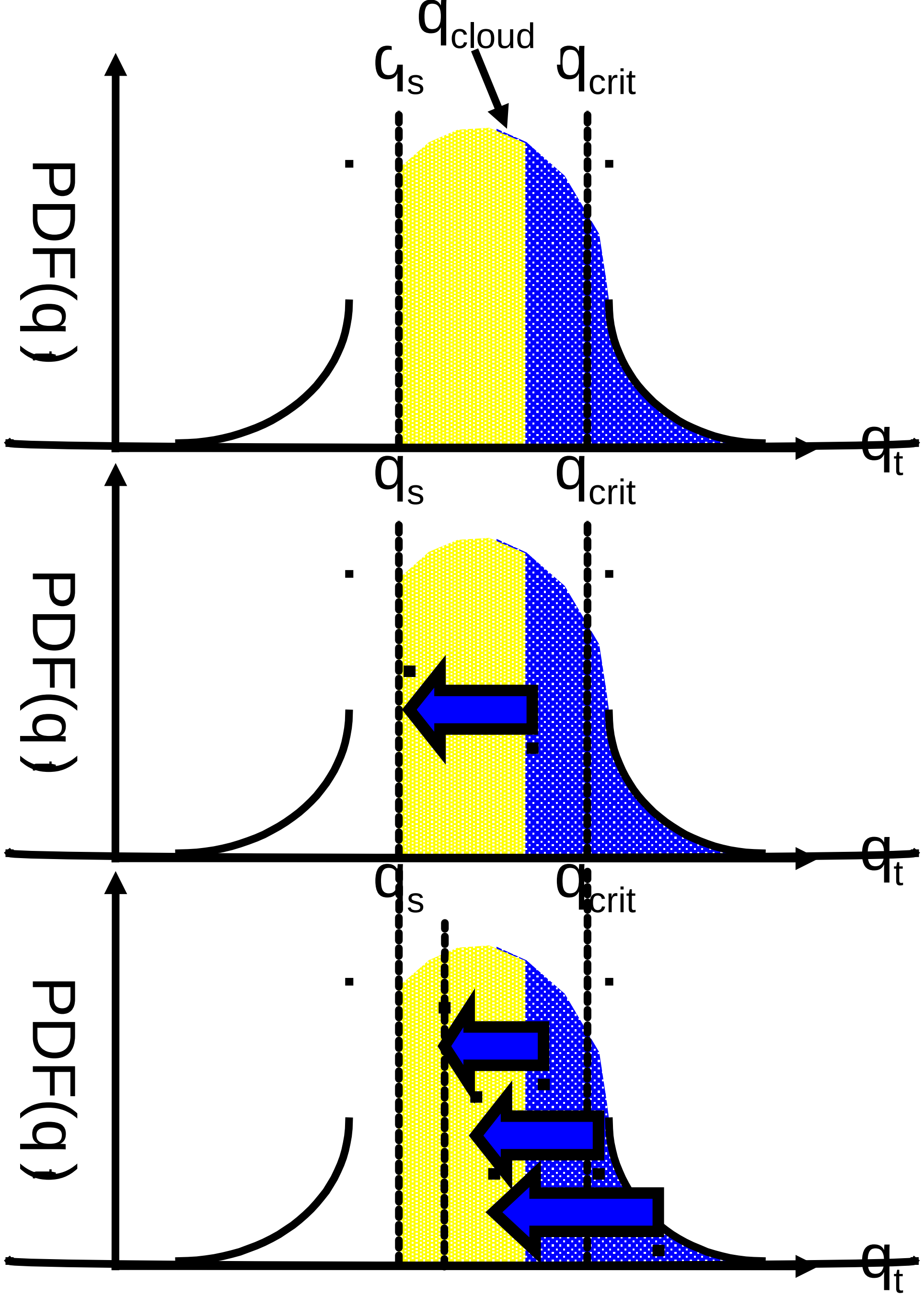
requires... more prognostic parameters!!!



- 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 process!

Statistical scheme framework, identical considerations!





Also, 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

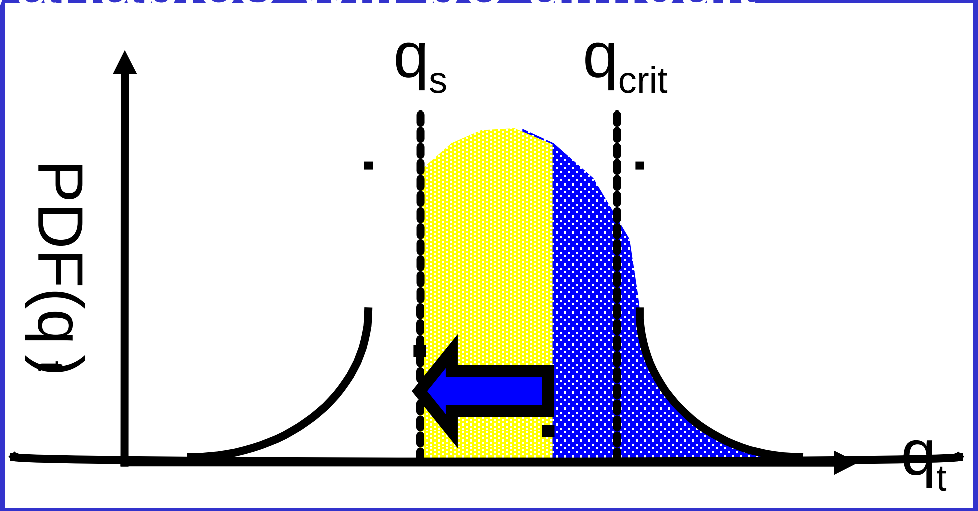
$$q_i = \int_{q_{cloud}}^{\infty} (q_t - q_s) PDF(q_t) dq_t$$

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

$$q_i = ???$$

The Future?

- Future development at ECMWF is likely to take the form of a hybrid scheme
- Prognostic equations for q_v, q_i/q_l, q_t, variance of q_t, but also C
- There is no redundancy between these variables if supersaturation is allowed
- However, writing sources terms self-consistently for these variables will be difficult



And what about mixed phase clouds?

- Rotstayn MWR (2000) – How would this be represented in a PDF framework?

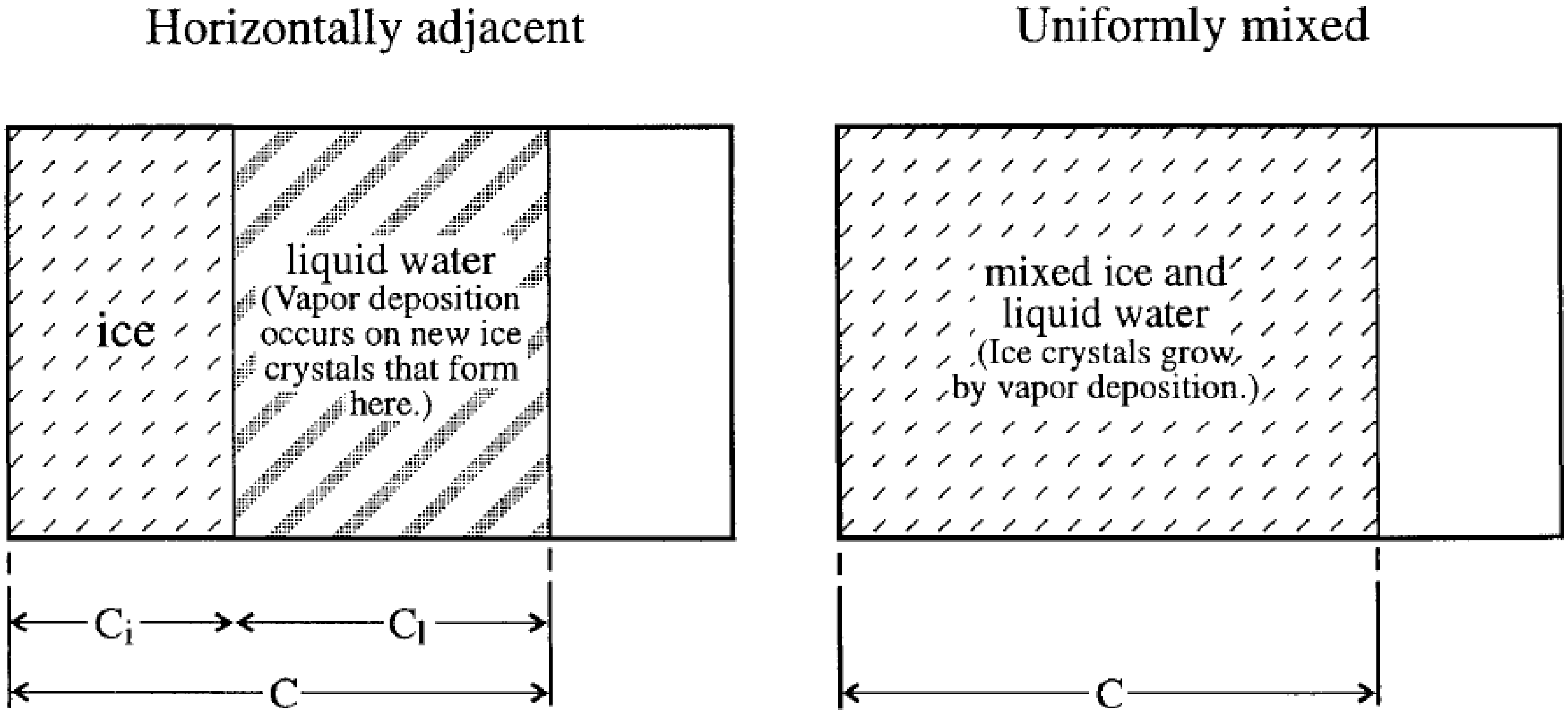


FIG. 2. Schematic illustration of the spatial relationship of cloud ice and cloud liquid water when using the horizontally adjacent and uniformly mixed assumptions.

Conclusions

- Partial cloud fraction is a result of thermodynamic variability on the subgrid-scale
- Any scheme that gives partial cloud cover makes implicit or explicit assumptions about fluctuations
- Explicit: Statistical schemes, with full “memory” of subgrid q_t state; useful info for other schemes
- But, assumption of no supersaturation is not good in ice phase
- Future schemes could be hybrid, combining cloud cover C with statistical approach to model ice