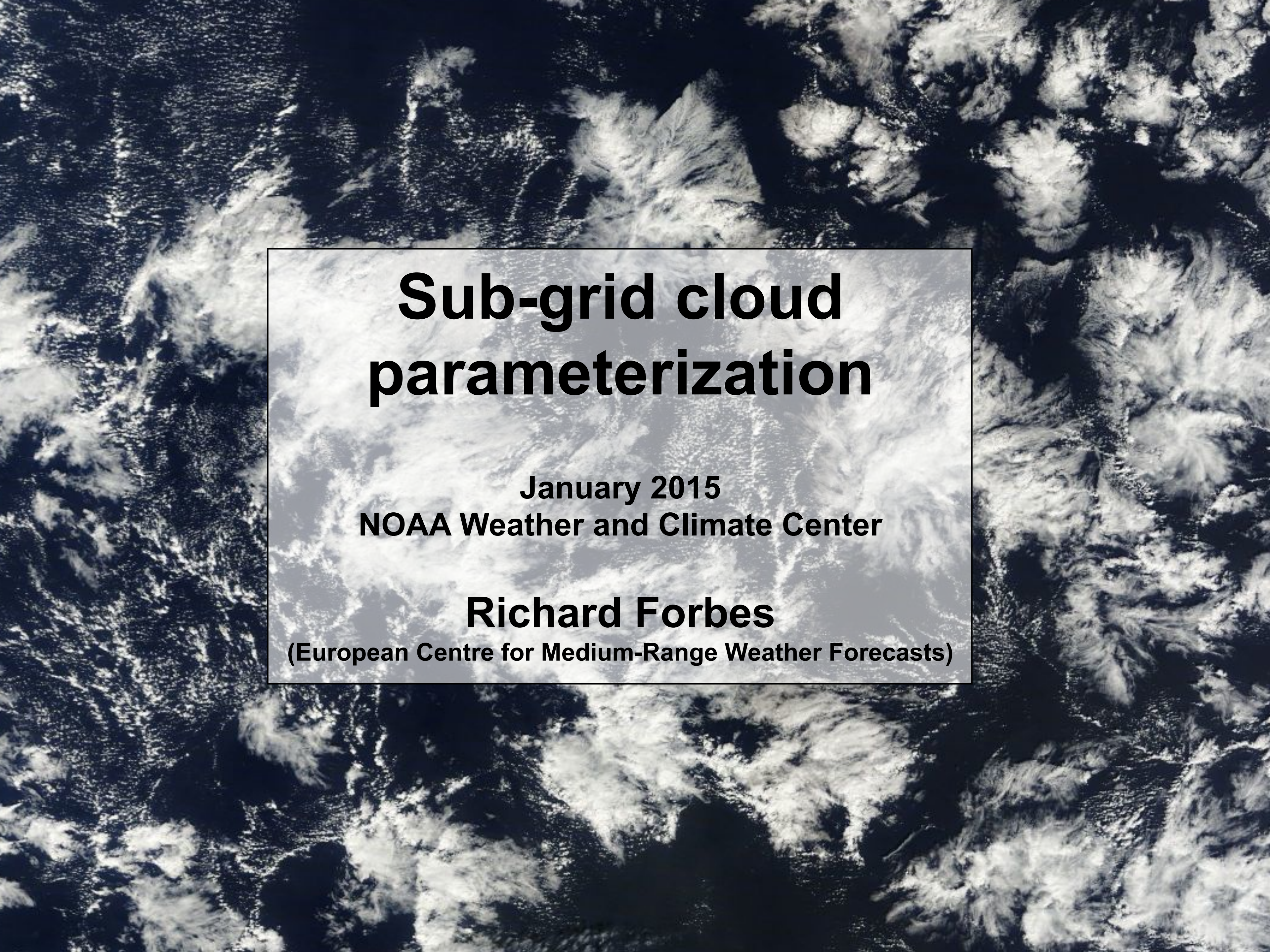


Sub-grid cloud parameterization

January 2015
NOAA Weather and Climate Center

Richard Forbes
(European Centre for Medium-Range Weather Forecasts)

Part I:

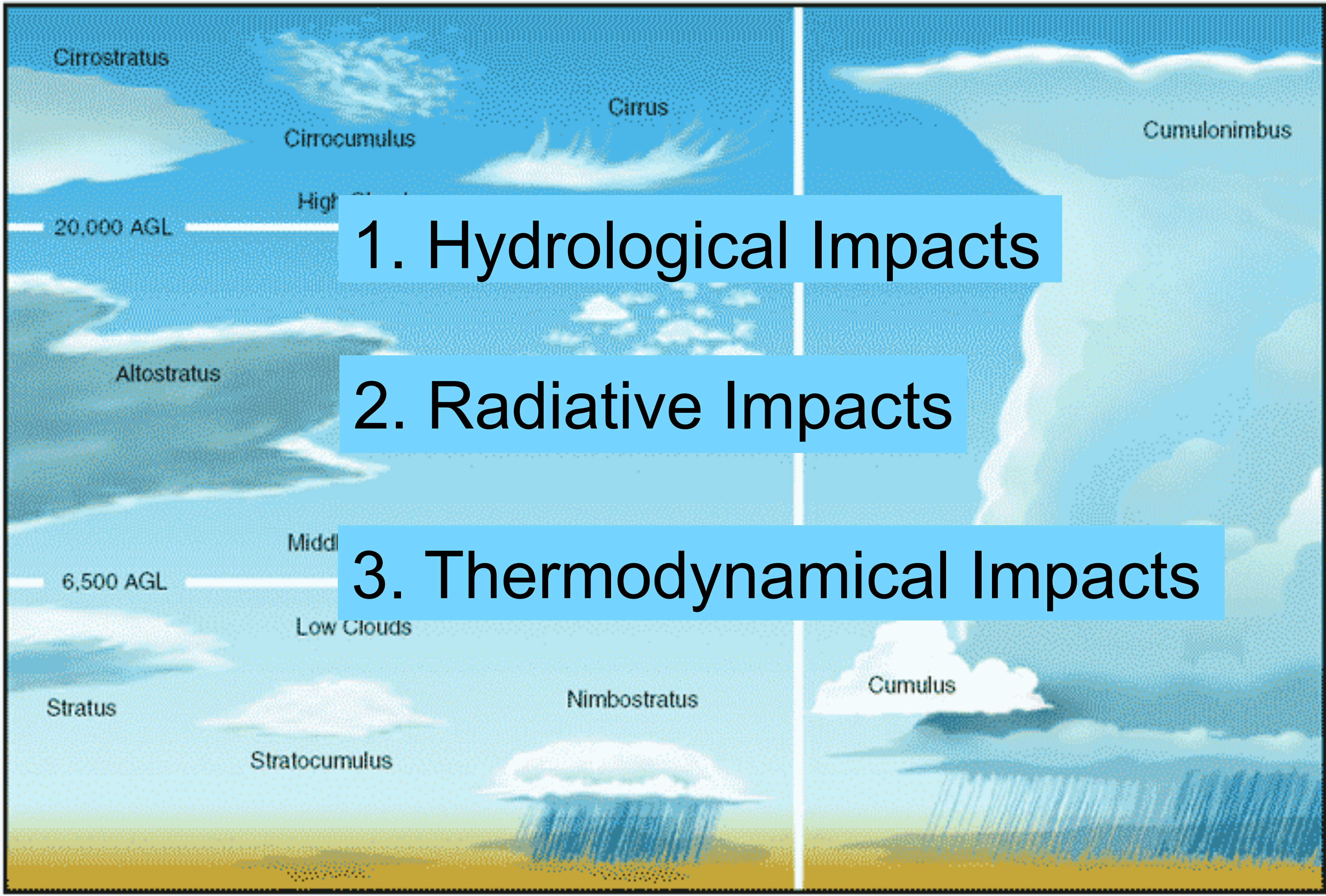
Clouds and scales of heterogeneity

Part II:

Representing sub-grid heterogeneity in models

Prospects

On the importance of clouds...

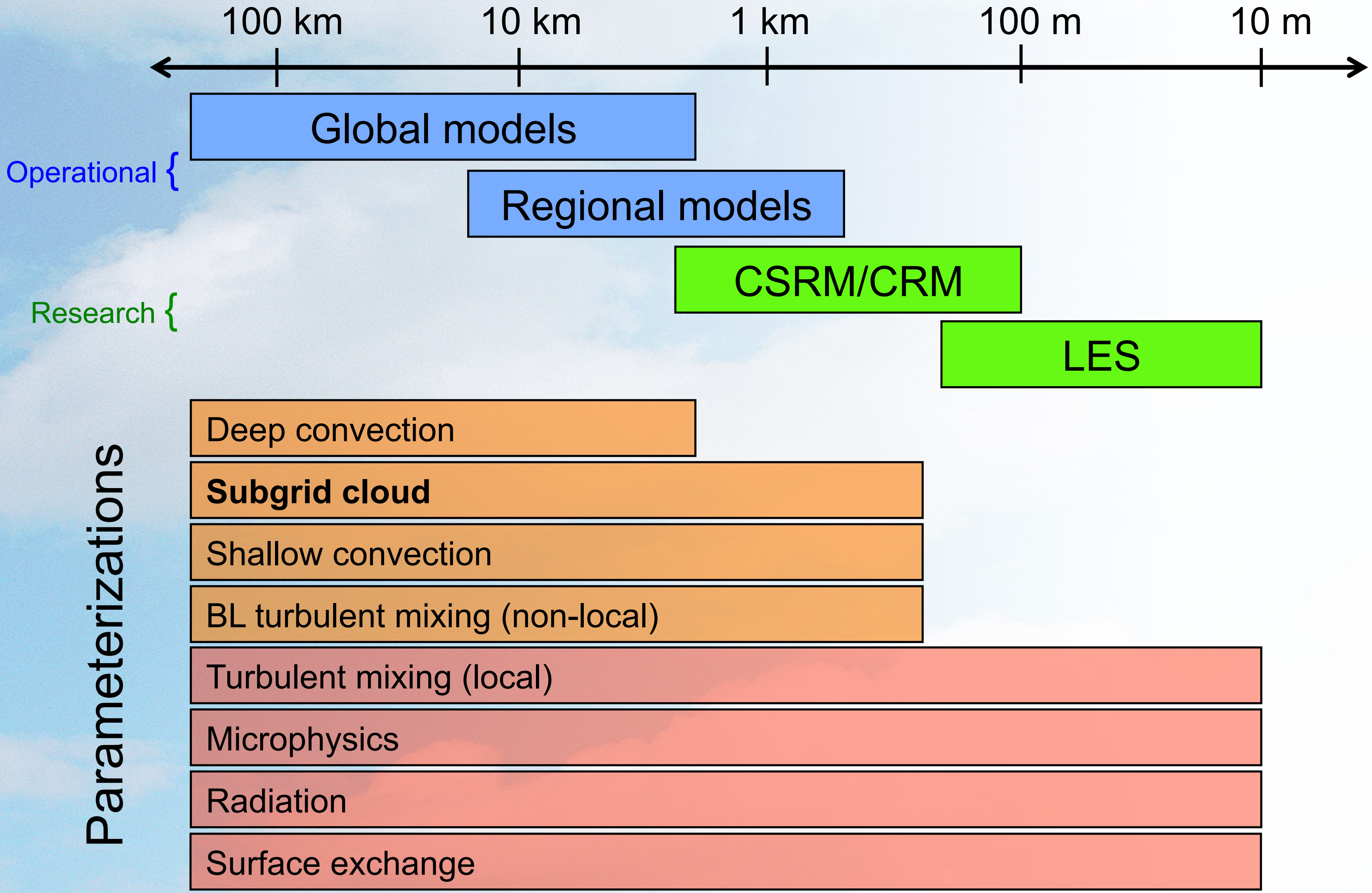


1. Hydrological Impacts

2. Radiative Impacts

3. Thermodynamical Impacts

On the importance of model resolution...



100 km

10 km

1 km

100 m

10 m

Operational {

Global models

Regional models

Research {

CSRM/CRM

LES

Parameterizations

Deep convection

Subgrid cloud

Shallow convection

BL turbulent mixing (non-local)

Turbulent mixing (local)

Microphysics

Radiation

Surface exchange

On the importance of representing subgrid cloud…

Subgrid Cloud = subgrid heterogeneity of water vapour & cloud condensate & temperature &…

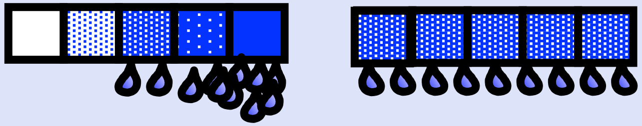
+ BL turbulence
+ Sh convection
+ deep convection

Cloud cover (latent heating)

Condensation before gridbox RH=100%
e.g. moist convective plume in dry environment

In-cloud microphysics (latent,hydrol)

Assuming homogeneity can lead to biased process rates, e.g. autoconversion, accretion, chemistry

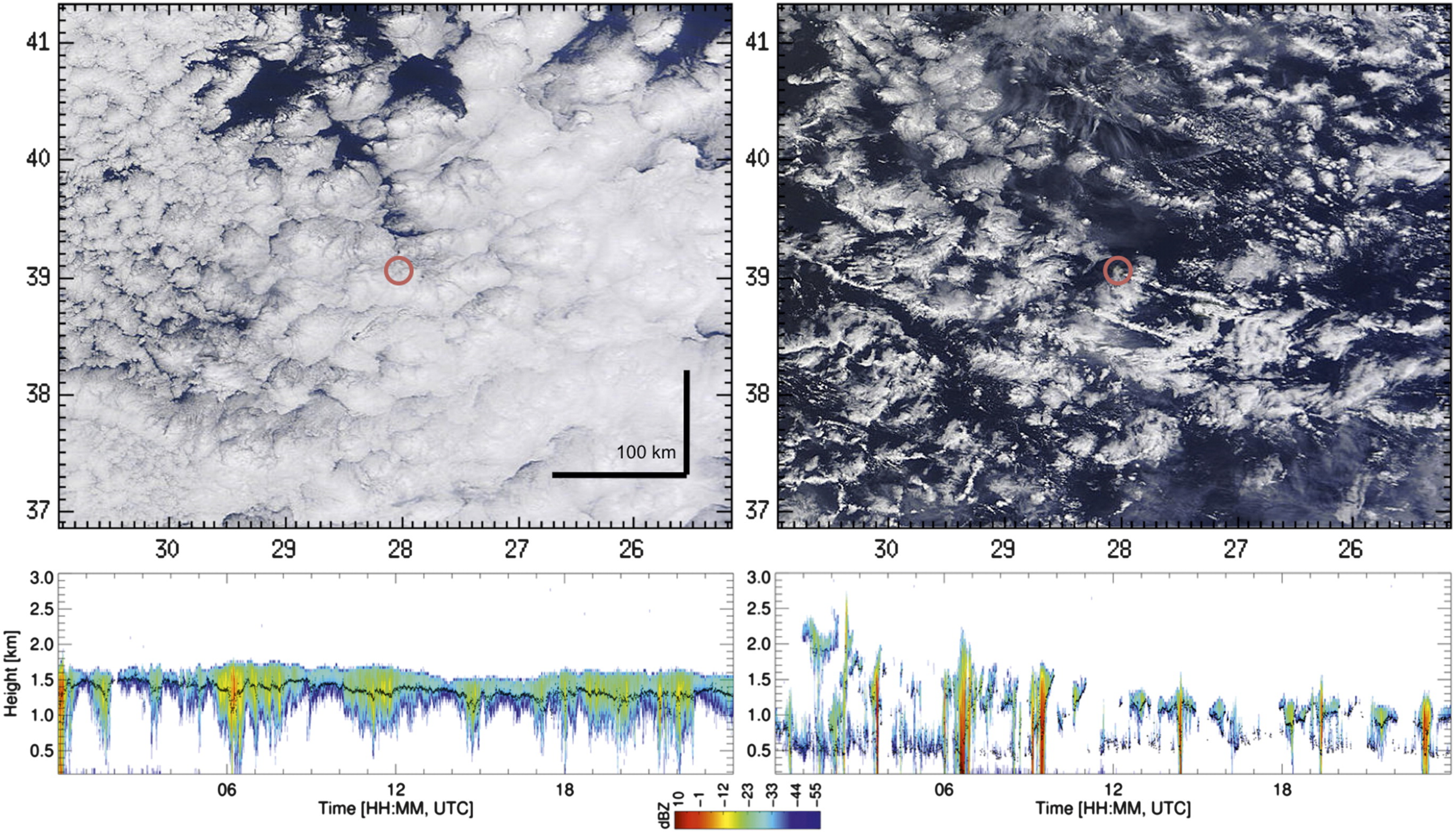


Can represent impact of heterogeneity with **analytical upscaling** (Larson & Griffin 2012; Boutle et al. 2013; Pincus and Klein 2000) or **Monte Carlo methods** (e.g. Larson et al. 2005)

Radiation (radiative)

Assuming homogeneity can lead to biased radiative calculations (e.g. Cahalan et al. 1994, Barker et al 1996). McICA.

Scales of variability
Radar data, Azores



Rémillard et al. (2012, JClim, Fig 2)

Important scales of cloud – global cover and reflectance

Wood and Field (2011, JClim,)

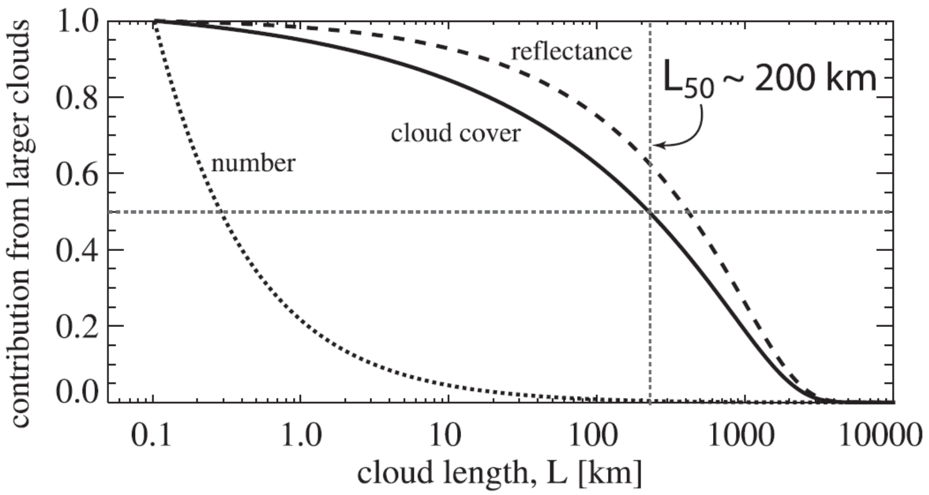


Fig 6. Contribution to global cloud cover (solid), number (dotted) and visible reflectance (dashed) from clouds with chord lengths greater than L (based on MODIS, aircraft and NWP data).

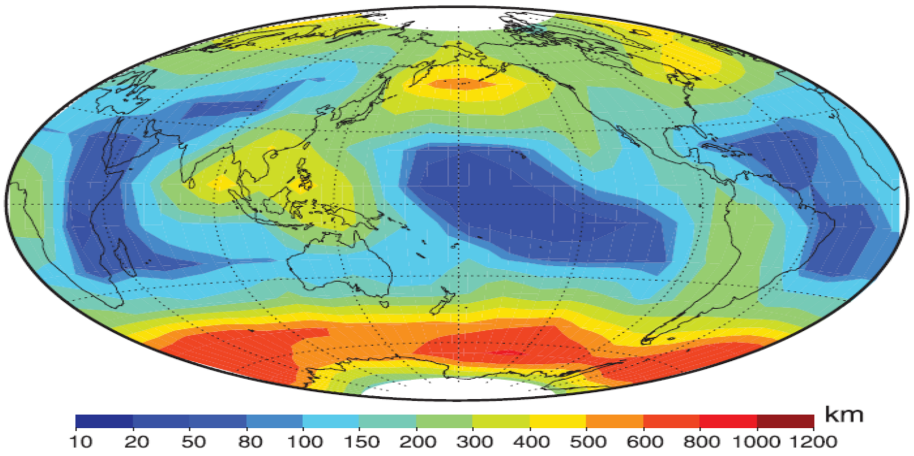
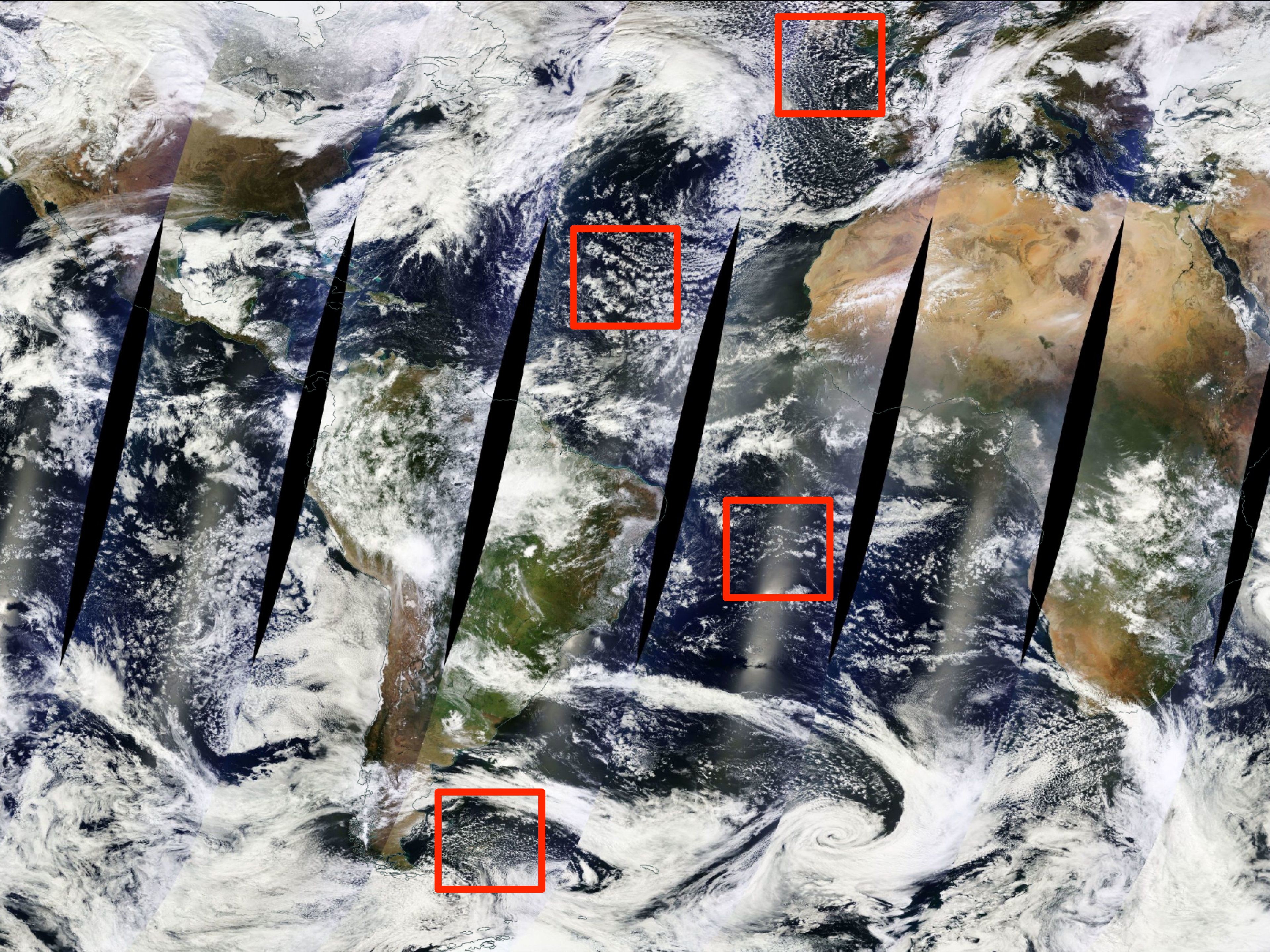


Fig 8. Map of the cloud size for which 50% of cloud cover comes from larger clouds (from 2 years of MODIS data)

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



Important scales of cloud – subgrid heterogeneity

Petch (2006, QJRMS)

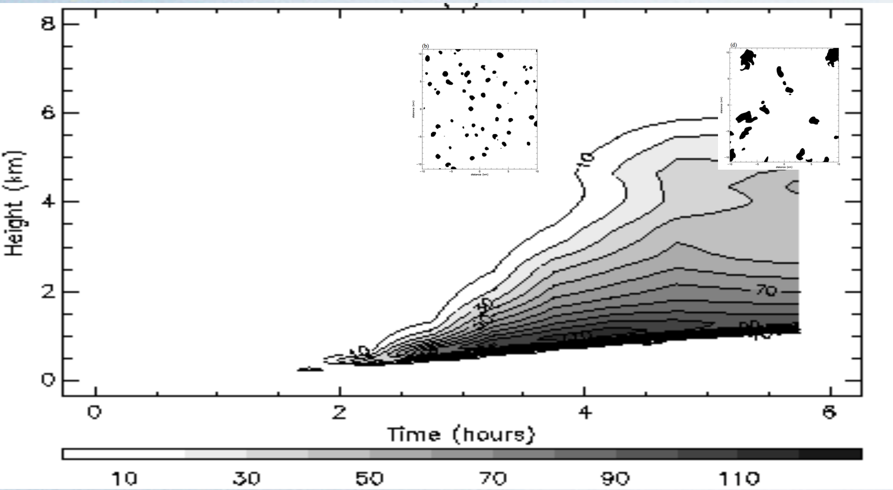


Fig 2. TRMM-LBA idealised diurnal cycle 3D CRM 100m resolution - growth of turbulent BL, shallow Cu transition to deep. Evolution of profile of upward mass flux with time.

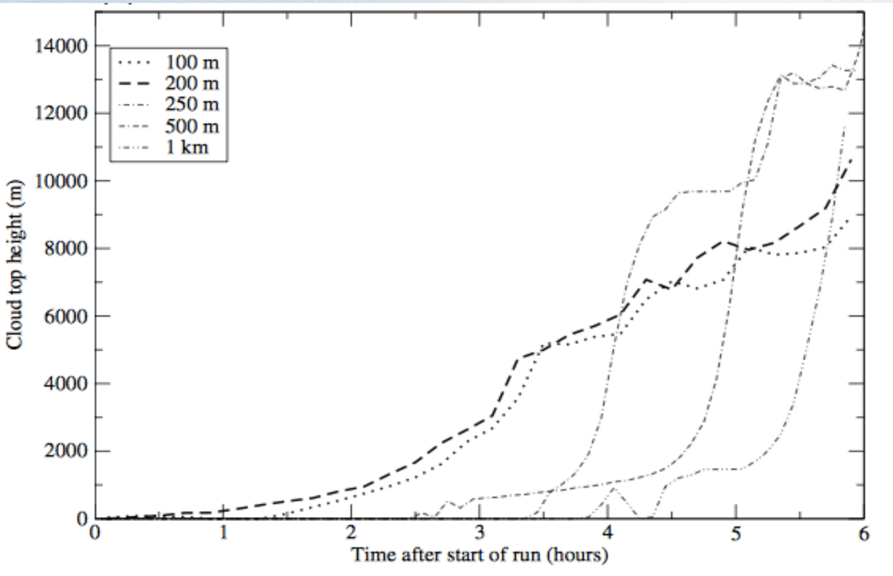


Fig 3. Evolution of maximum cloud top height for different resolutions from dx=100m to dx=1km

Need ~100m resolution before start to get convergence

Summary Part I

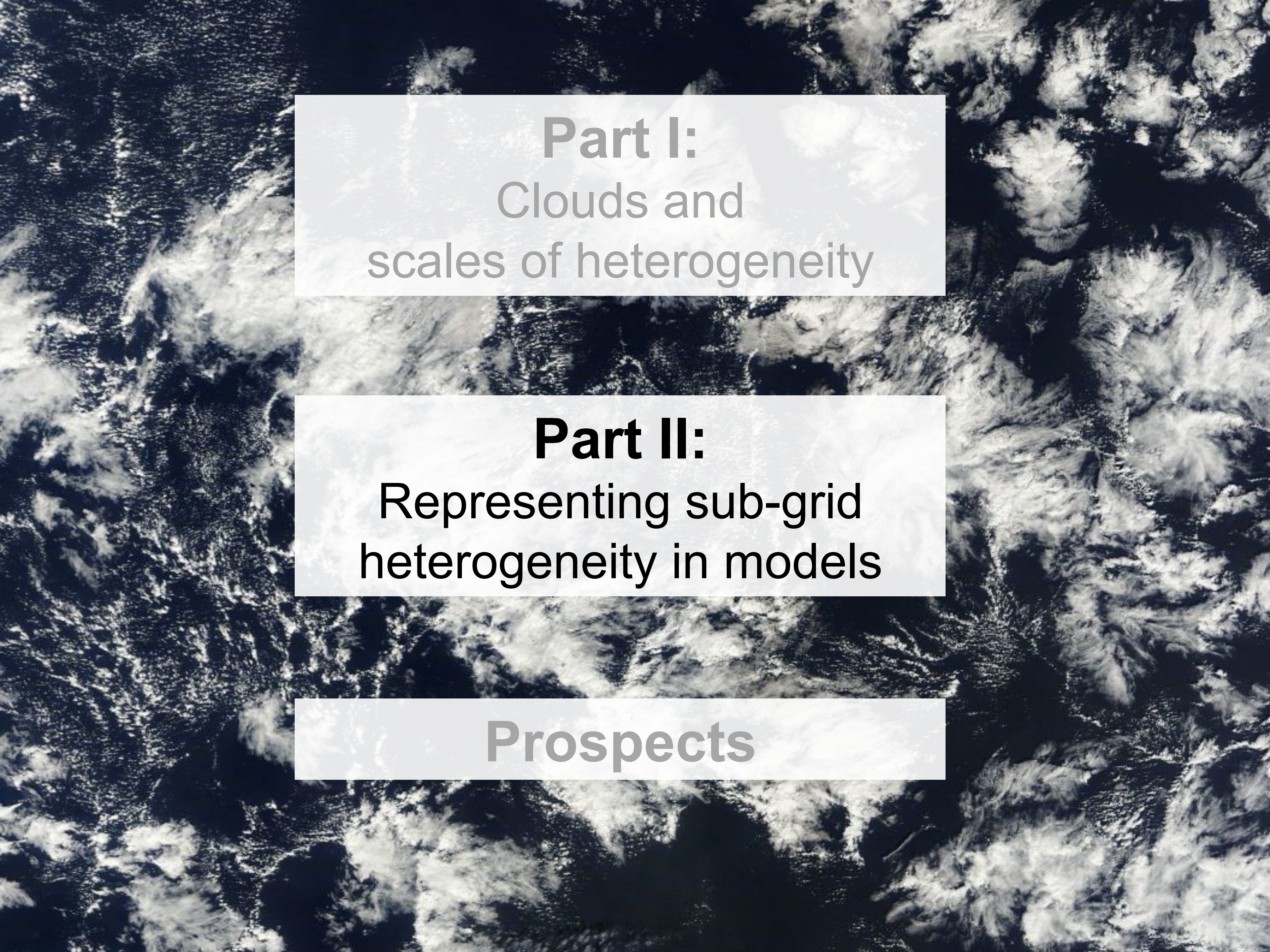
1. Cloud important for radiation, dynamical impacts (latent heating), hydrological impacts (precipitation) and chemistry.

2. Model resolution increasing - traditional compartmentalisation into BL turbulence, convection and subgrid cloud less clear.

3. Subgrid scale heterogeneity needed for condensation, radiation, microphysics/chemistry.

4. Unresolved clouds become less important with increasing model resolution, **but** still important for sub-10km, particularly in boundary layer cloud regimes.

5. Scales of BL turbulence/convection/cloud all linked. Need 100m before can treat model as all or nothing?



Part I:
Clouds and scales of heterogeneity

Part II:
Representing sub-grid heterogeneity in models

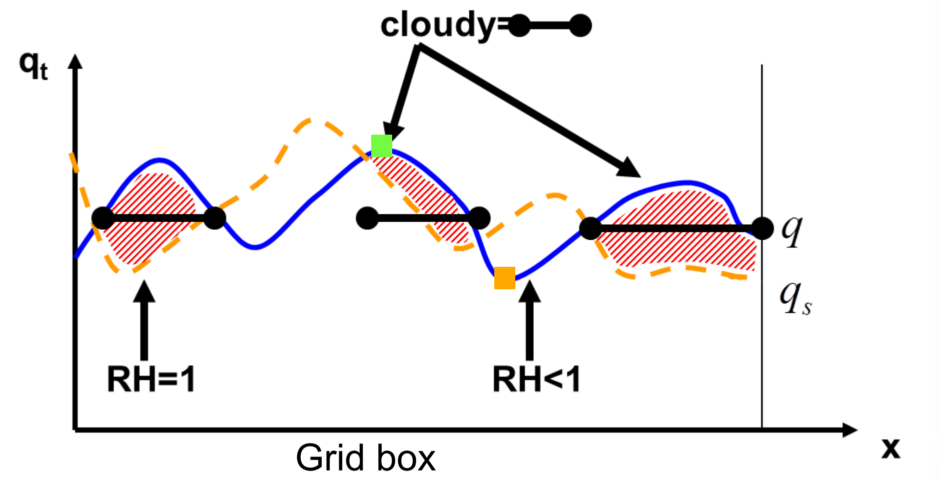
Prospects

Representing unresolved heterogeneity

Statistical schemes explicitly specify the probability density function (PDF), *G*, for quantity, *s*, (or if assume T homogeneous, total water q_t)

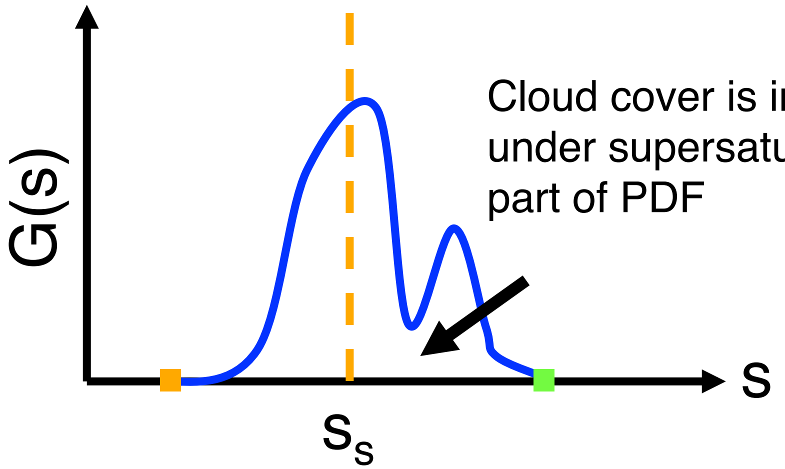
(Sommeria and Deardorff 1977; Mellor 1977)

$$s = a_L(q_t - \alpha_L T_L) \qquad s' = a_L(q_t' - \alpha_L T_L')$$



Cloud cover $\displaystyle\int_{s_s}^{\infty} G(s)\,ds$

Condensate $\displaystyle\int_{s_s}^{\infty} (s - s_s)G(s)\,ds$



Cloud cover is integral under supersaturated part of PDF

Representing unresolved heterogeneity

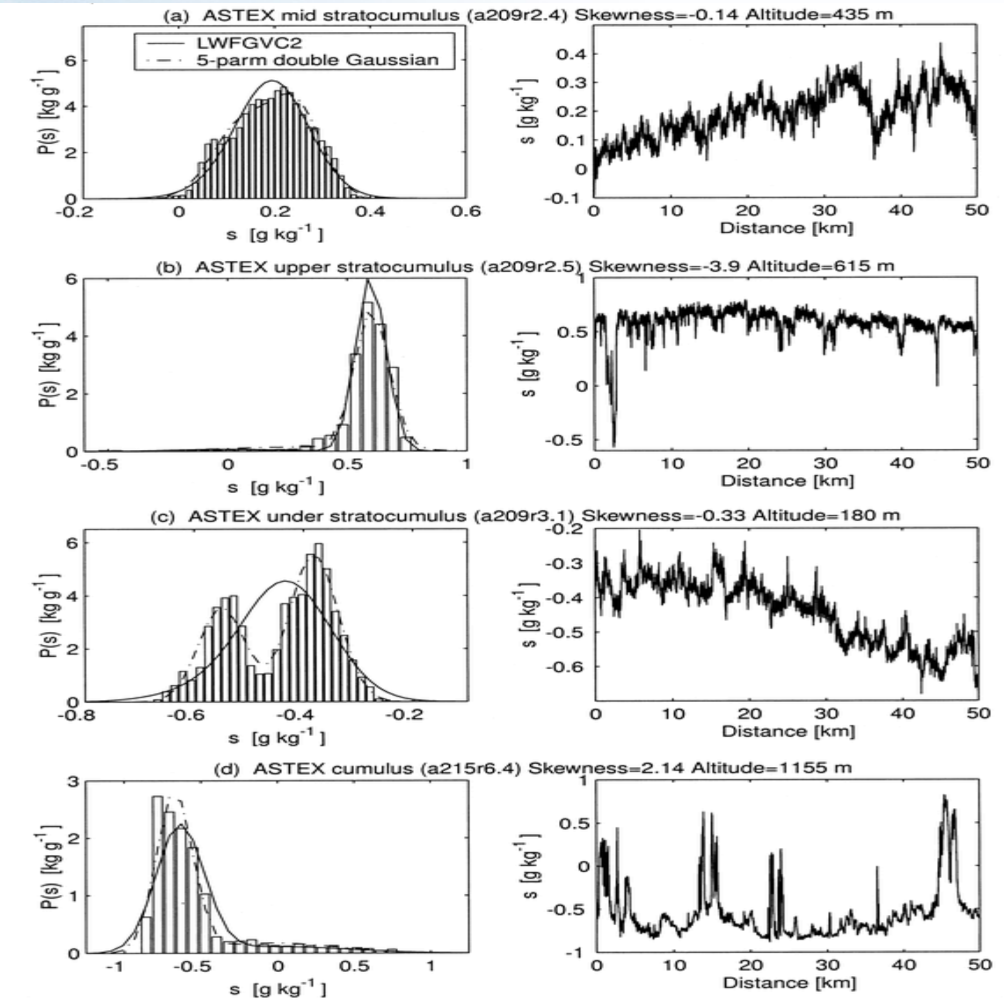
Observations from aircraft, tethered balloon, satellite, Raman lidar

…and LES model data…

…suggest PDFs can generally be approximated by uni or bi-modal distributions, describable by a few parameters

Observations from aircraft (Larson et al. 2001)

PDF Data



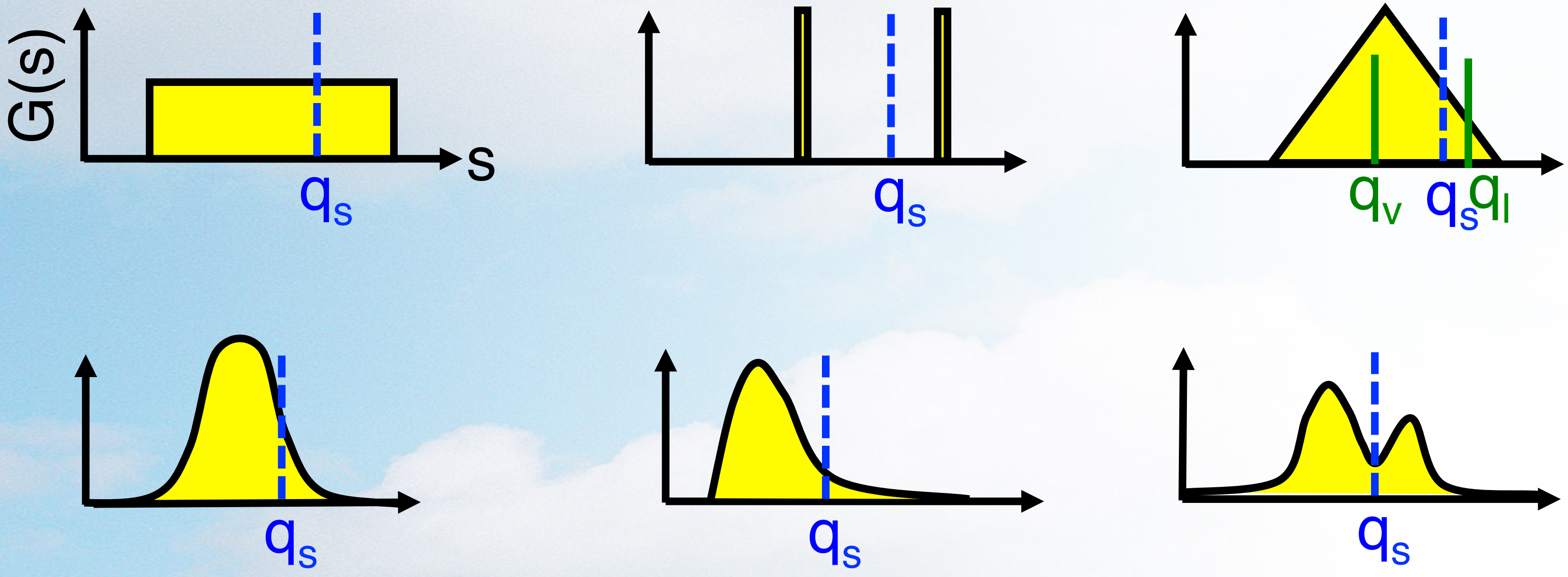
Building a statistical cloud scheme

Need to represent with a functional form, specify the:

(1) PDF type (delta, continuous, unimodal, bimodal, symmetrical, bounded?)

(2) PDF variables (mean, variance, skewness / vapour, condensate, cloud fraction ?)

(3) Diagnostic or prognostic (how many degrees of freedom?)

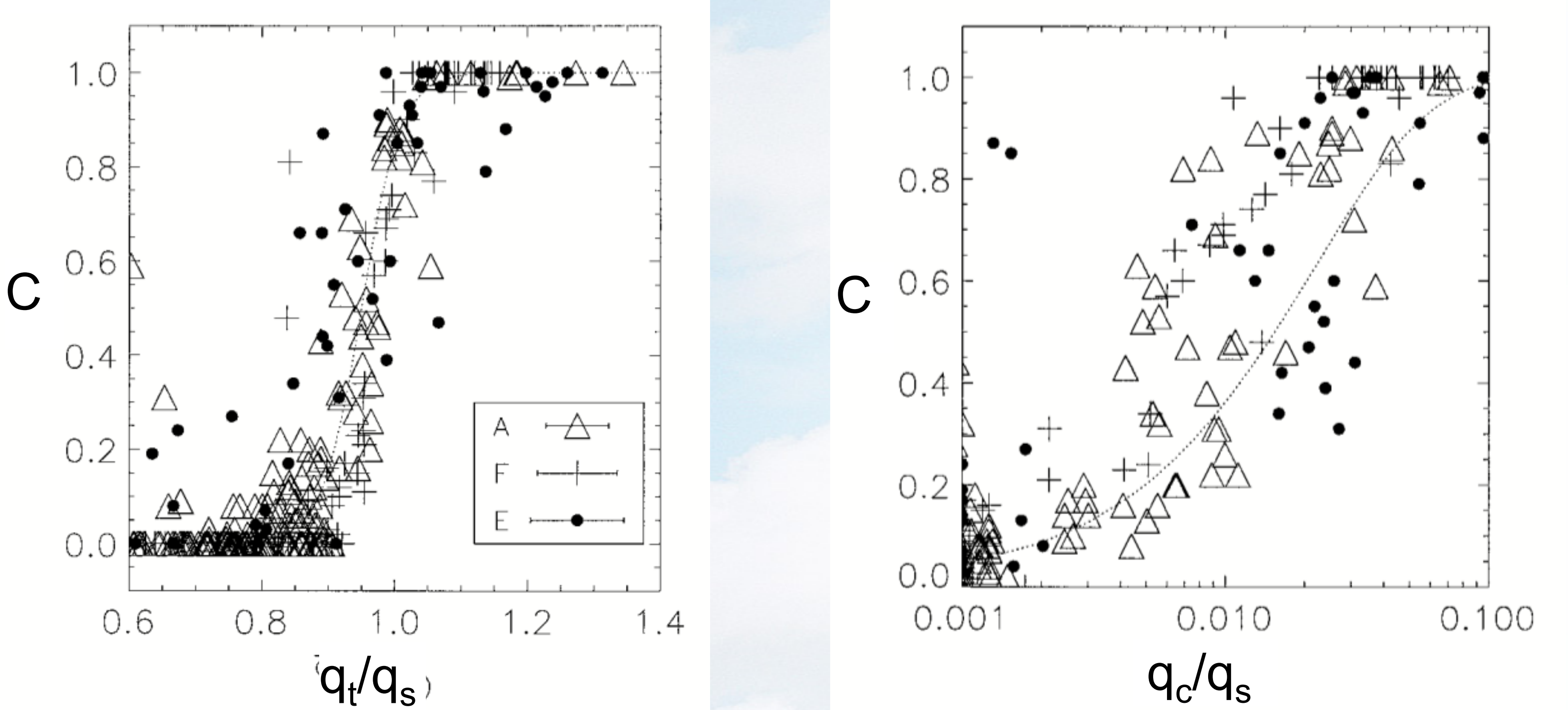


Building a statistical cloud scheme

Note, any function that has a fixed width has only one degree of freedom for determining cloud fraction, i.e. C=fn(RH), a “relative humidity” scheme.

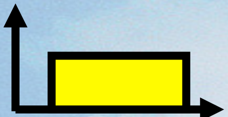
A reasonable first approximation, but in reality, different cloud fractions and condensates observed for a given RH

Aircraft data from Wood and Field (2000)

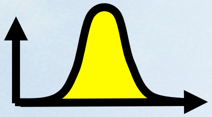


A few forms of "assumed PDFs" in the literature…

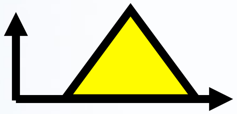
(by no means exhaustive!)



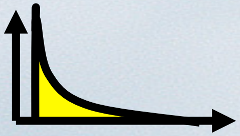
Uniform:
Sundquist (1978)
Letreut and Li (1991)



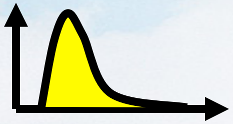
Gaussian:
Sommeria and Deardorff (1977)
Mellor (1977)



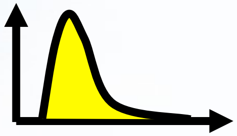
Triangular:
Smith (1990)



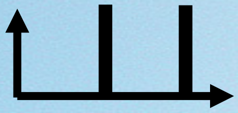
Exponential:
Bougeault (1981)



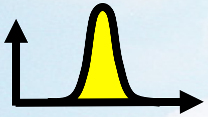
Lognormal:
Bony and Emanuel (2001)



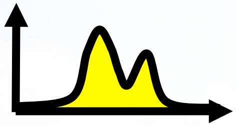
Gamma:
Bougeault (1982)
Barker et al. (1996)



Double Delta Fn:
Randall et al. (1992)
Lappen and Randall (2001)



s4 polynomial:
Lohmann et al. (1999)



Double Gaussian (binormal):
Lewellen and Yoh (1993)
Larson et al. (2001)
Golaz et al. (2002)

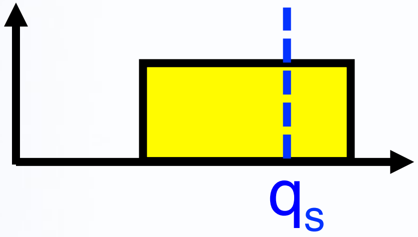
Sundquist (1989) – form used in many GCMs

(1) Uniform

(2) Prognostic: Total water mean

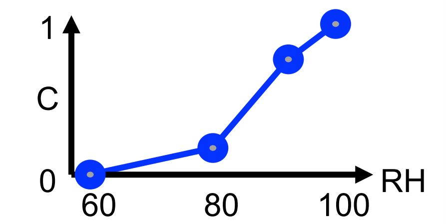
Diagnostic: Variance (width)

(3) 1 cloudy degree of freedom + BL + convection



Advantages:

- First order approximation to obs
- Computationally inexpensive



Disadvantages:

- Not enough degrees of freedom (tied to RH)
- Requires RHcrit to specify width when clear sky
- Not all processes are formulated with the PDF
- Doesn't allow skewness

Can be shown to be equivalent to "relative humidity" scheme

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

Other schemes:

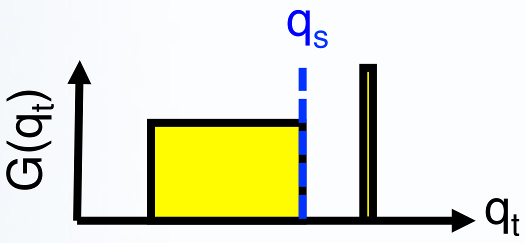
- Smith (1990) Met Office LAMs triangular distribution
- Xu and Randall (1996) extended to C=fn(RH,qc)

Tiedtke (1993) ECMWF operational IFS since 1995

(1) Uniform/delta function

(2) Humidity mean, condensate mean, cloud fraction

(3) 3 cloudy degrees of freedom + BL + convection



Advantages:

- Computationally inexpensive
- Sources and sinks for all processes
- Direct convective detrainment of condensate and cloud fraction important term
- In principle, allows positive and negative skewness
- Number of tunable parameters

Disadvantages:

- Number of tunable parameters
- Not continuous PDF, no condensate heterogeneity
- Requires RHcrit to specify “top-hat” width when clear sky
- Not all processes are formulated with the PDF, some adhoc
- Not reversible in condensation/evaporation

Other schemes:

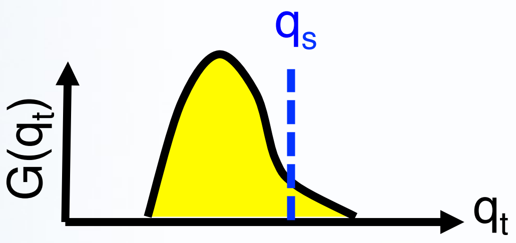
- PC2 Met Office global (Wilson et al. 2008) – more consistently formulated

Tompkins (2002) ECHAM

(1) Bounded Beta function with positive skewness

(2) Prognostic: Total water mean, condensate mean, upper bound

(3) ~3 degrees of freedom + convection



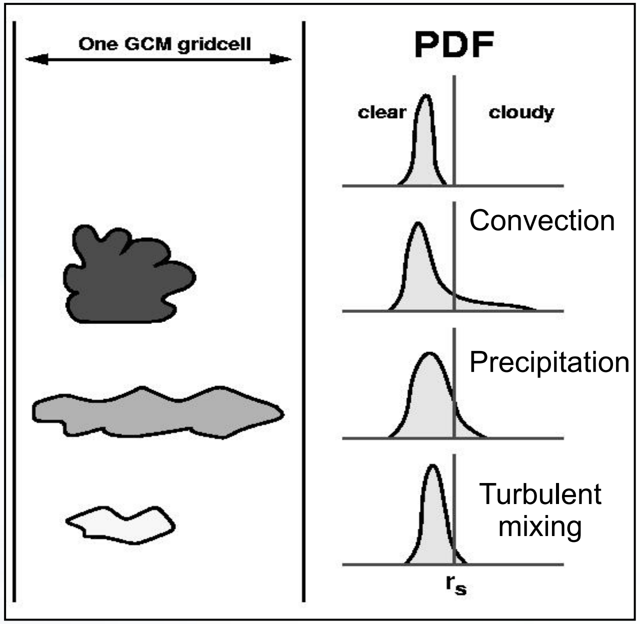
Advantages:

- Continuous bounded function, closer fit to obs
- Allows skewness
- Turbulence directly affects variance
- Treats sources/sinks other than turbulence (e.g. precipitation, convective detrainment)

Disadvantages:

- Assumes homogeneous temperature
- Some of the sources and sinks are rather ad-hoc in their derivation.

- Implemented in ECHAM but positive skewness only (Weber et al. 2011)



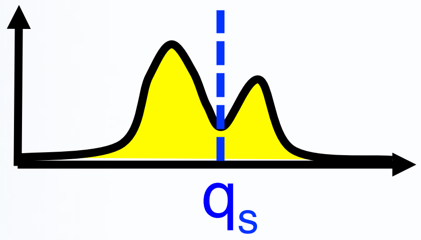
Golaz et al. (2002), CLUBB

(1) Joint double Gaussian P(w, θ_l, q_t)

(2) Prognostic: $w, \theta_l, q_t, w'^2, \theta_l'^2, q_t'^2, w'\theta_l', w'q_t', \theta_l'q_t', w'^3$

Diagnostic: other third order moments

(3) 10 degrees of freedom (6 cloudy?)



Advantages:

- Unifies treatment of boundary layer turbulence, shallow conv & subgrid cloud
- Both shallow Cu and Sc clouds described by a single consistent equation set. (Golaz et al. 2002; 2007; Larson and Golaz 2005, Larson et al. 2012)
- Flexible PDF fits observations (Larson et al. 2001)
- Use w for aerosol activation?
- Tested in WRF, CAM (Bogenschutz et al. 2013), GFDL (Guo et al. 2014)

Disadvantages:

- Computationally expensive (7 new prognostic equations)
- Needs short timestep (seconds)
- Doesn't contain effects of all processes (ice supersaturation, precipitation)

Other schemes:

- Bogenschutz and Krueger (2013) – simplified and computationally efficient rewrite making higher order moments diagnostic – needs good SGS TKE

Summary Part II

1. Obs suggest PDFs can generally be approximated by uni or bi-modal distributions, describable by a few parameters.

2. Almost all schemes can be formulated in terms of an "assumed PDF", but vary widely in PDF form, diagnostic and prognostic variables and degrees of freedom.

3. Need sufficient degrees of freedom to represent the observed variability.

4. High order closure schemes unifying treatment of BL, Sh Cu and subgrid cloud very promising, and now being implemented in GCMs, and being made more efficient.

5. Specification of sources and sinks is important. Performance outside BL? Ice/mixed phase?

Part I:
Clouds and
scales of heterogeneity

Part II:
Representing sub-grid
heterogeneity in models

Prospects

Prospects for representing unresolved (cloudy) heterogeneity

Key driving concepts for the parametrization of subgrid heterogeneity

- Fidelity – improved realism
- Consistency – across parametrizations
- Convergence – across resolutions
- Complexity vs Cost vs Uncertainty
- Impacts? – radiative, thermodynamical, hydrological

Prospects for representing unresolved (cloudy) heterogeneity

Some summary comments:

- BL turbulence, shallow convection, deep convection, cloud scheme are all part of the sub-grid problem.

- Representing sub-grid cloud gets less important as models go to higher resolution, but still required sub-10km. Should have some representation of sub-grid heterogeneity possibly down to dx=~100m?

- High order closure turbulence schemes unifying BL/Cu processes with assumed PDF work well for liquid-phase turbulent boundary layers with resolution independence, but complexity(?), computational cost(?), only part of the solution (what about deep convection, outside BL?)

- Not so straight forward for including subgrid ice phase, mixed-phase and precipitation, vertical overlap.

- Avoid mixing cloud schemes for different parts of the model.

- Conceptual framework important, but details matter – sources and sinks, numerical solutions.