ECMWF

Numerical Weather Prediction
Parametrization of Subgrid Physical Processes

Clouds (3)
Sub-grid heterogeneity of clouds

Richard Forbes

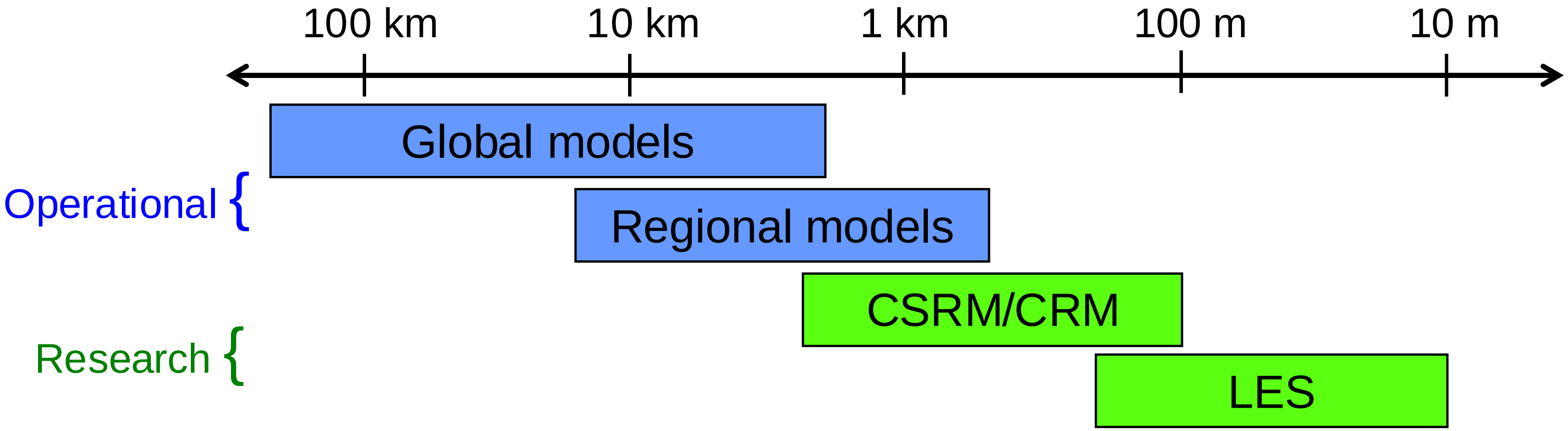
(With thanks to Adrian Tompkins, Christian Jakob, Maike Ahlgrimm)

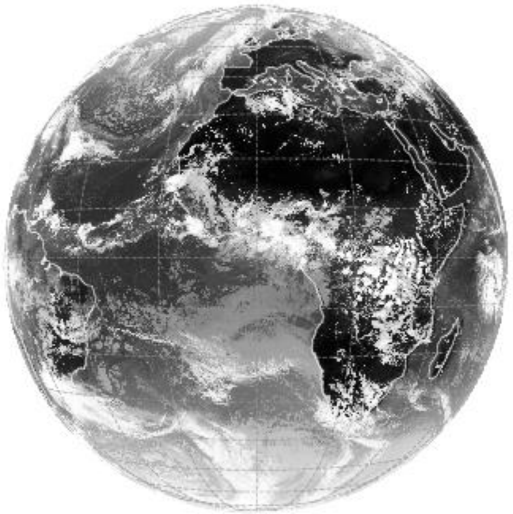
(1) Scales of heterogeneity and why they matter

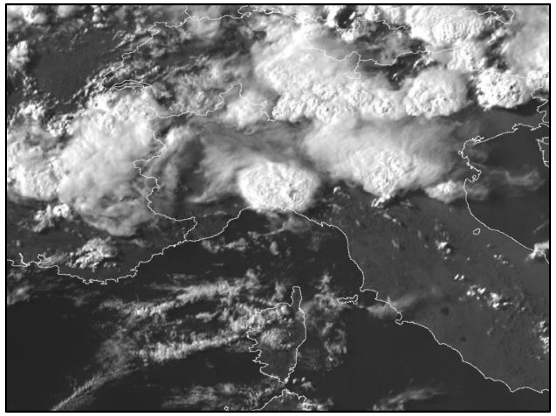
(2) Representing sub-grid heterogeneity in models

(3) Summary

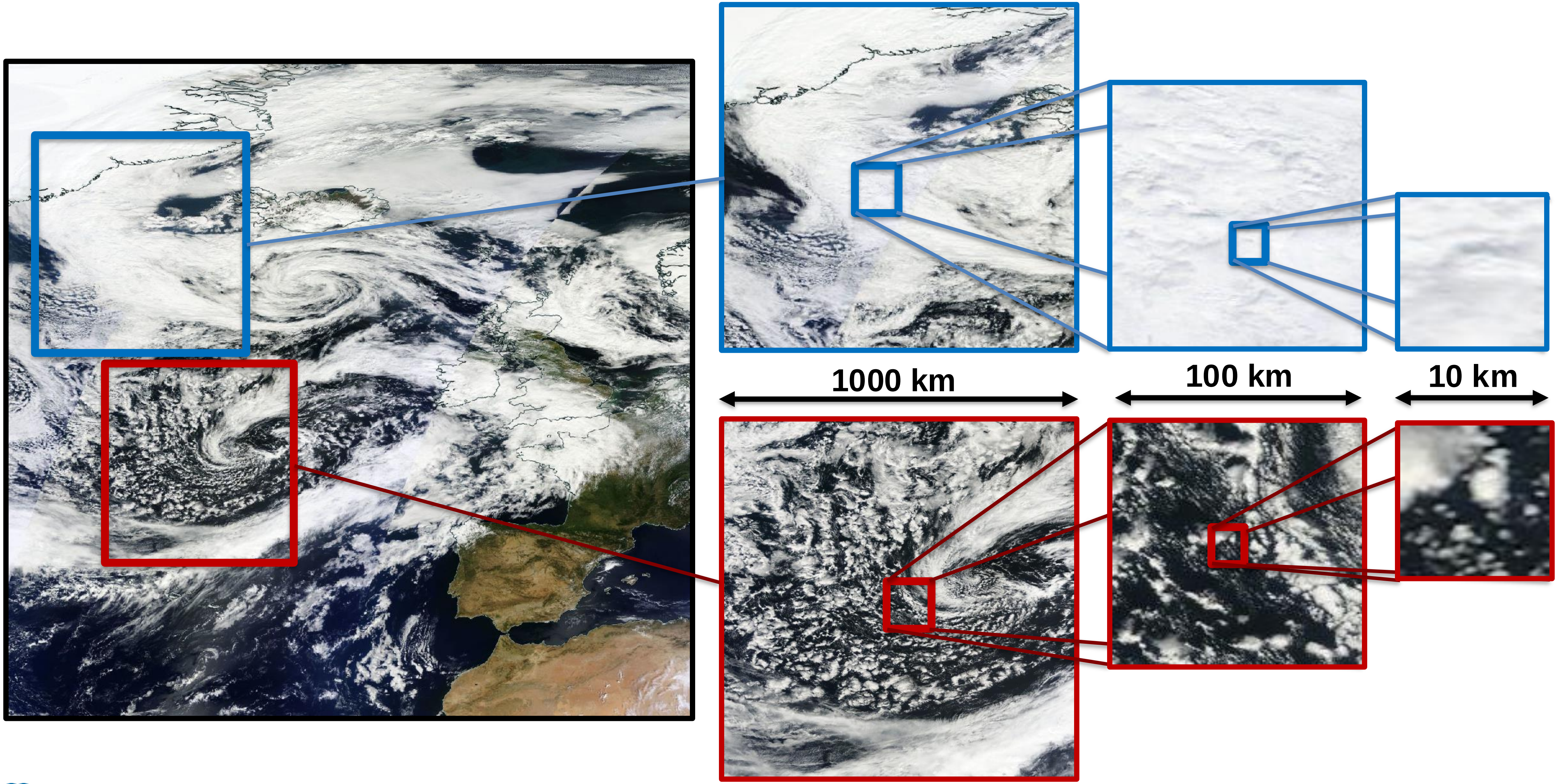
Scales of heterogeneity: Wide range of model resolutions





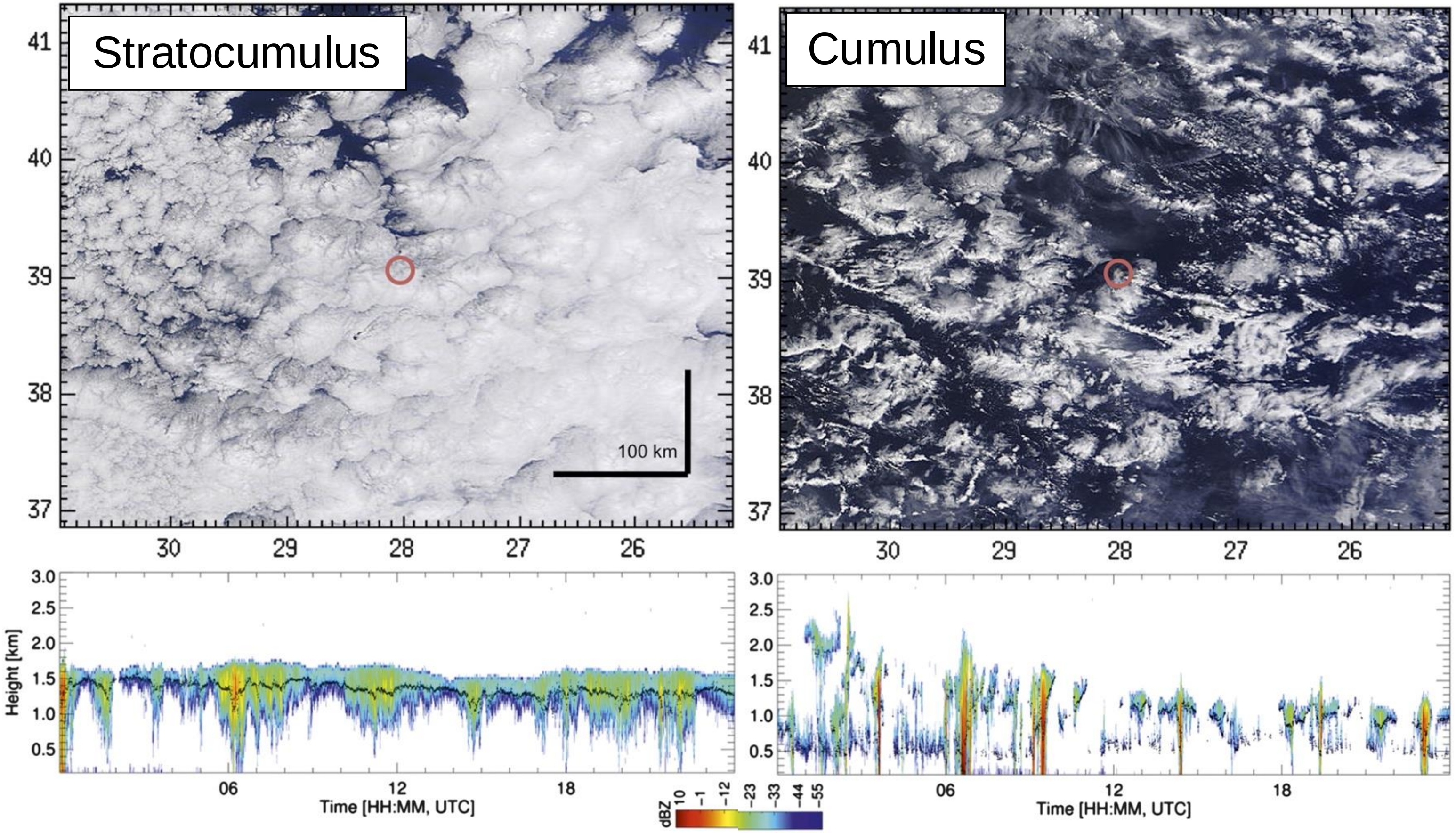


Scales of heterogeneity: Significant across scales – cloudy/clear *and* in-cloud

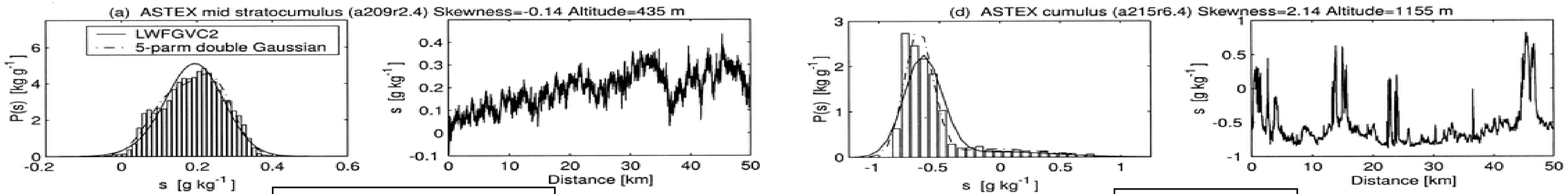


Scales of heterogeneity: Humidity, cloud and precipitation ←→ turbulence

North Atlantic, Azores
MODIS and radar data
Rémillard et al. (2012)



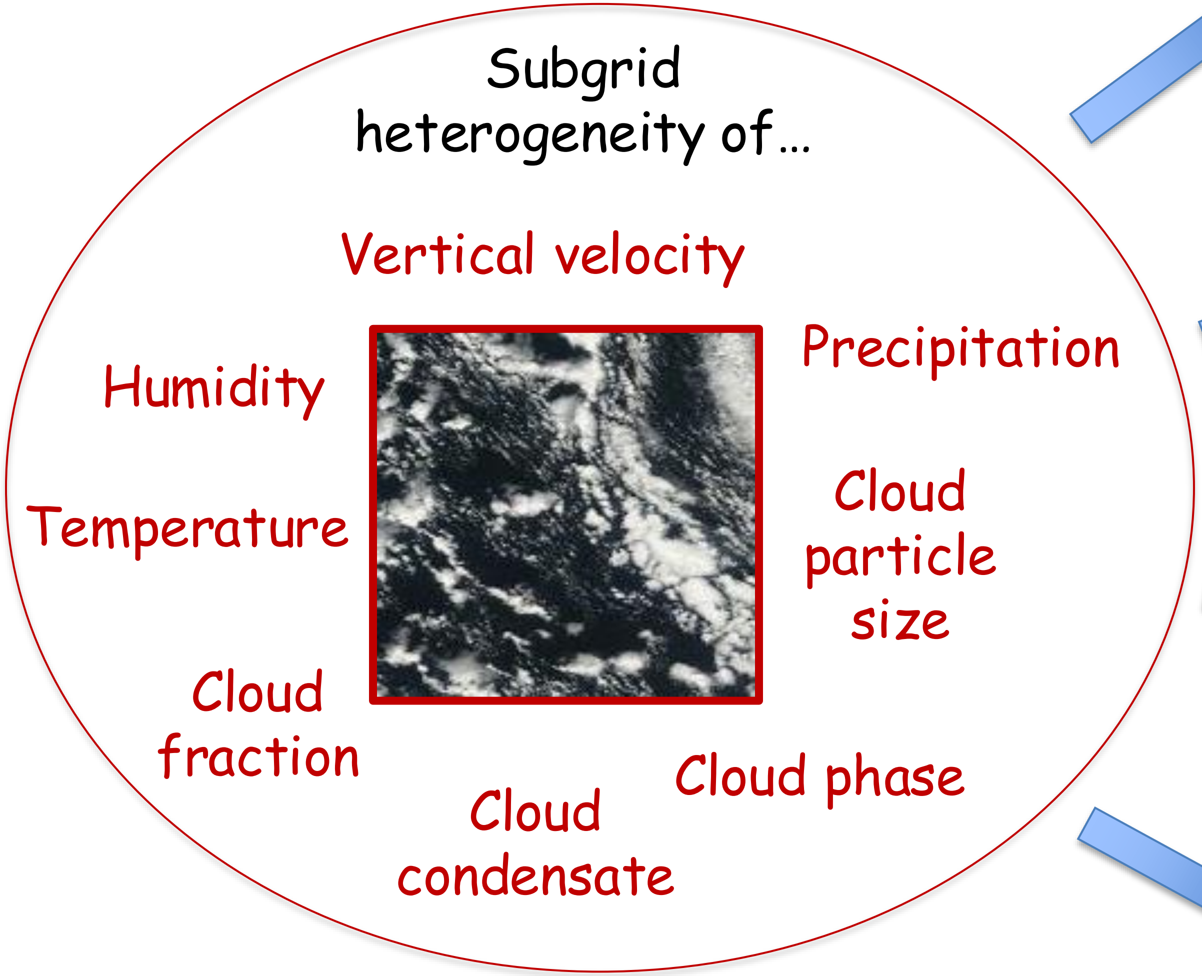
ASTEX aircraft data
(Larson et al. 2001)



Stratocumulus

Cumulus

Scales of heterogeneity: Impacts on radiation, precipitation, latent heating



Radiative Impacts

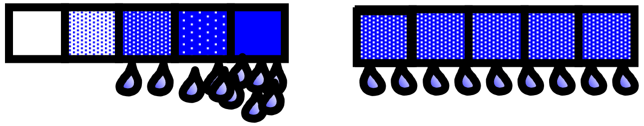
Cloudy sky versus clear sky fraction matters

Assuming homogeneity → radiation biases

Overlap of cloud in the vertical

Hydrological Impacts

Rain formation related to subgrid liquid water contents



Thermodynamical Impacts

Condensation occurs before gridbox RH=100%

Evaporation in clear sky fraction

Transport, Chemistry

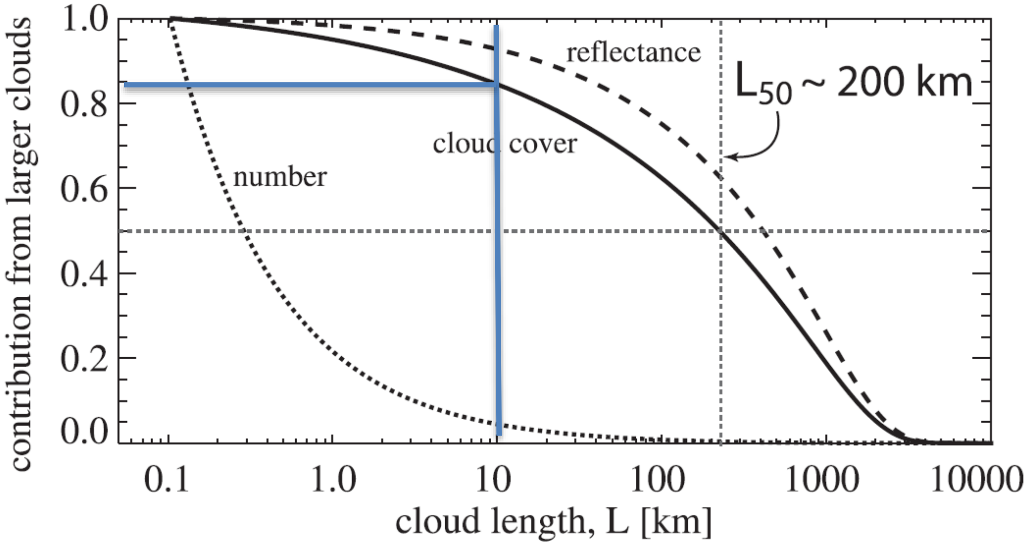
Cloud associated with dynamics (T, q, u, v, w)

Chemistry in clouds

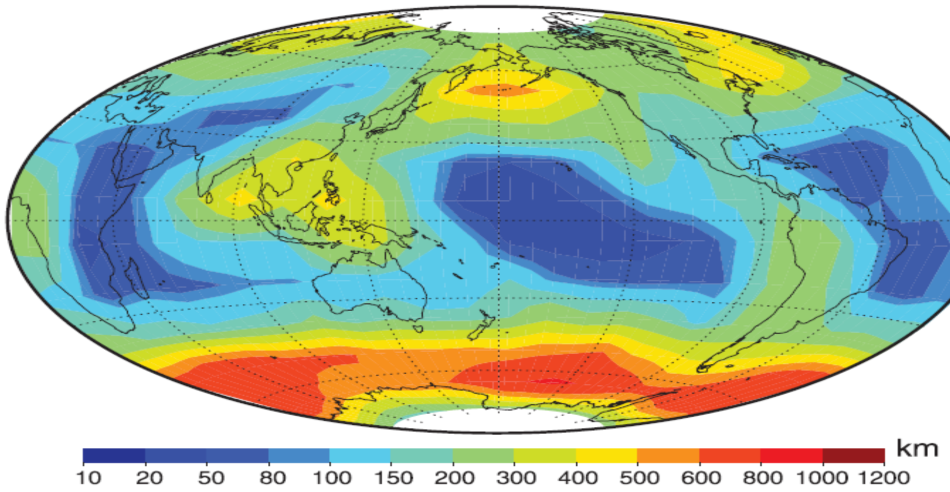
Scales of heterogeneity: Global cloud cover and reflectance

From Wood and Field (2011, JClim)

Contribution to global cloud cover, number and visible reflectance from clouds with chord lengths greater than L (from MODIS, aircraft & NWP data).

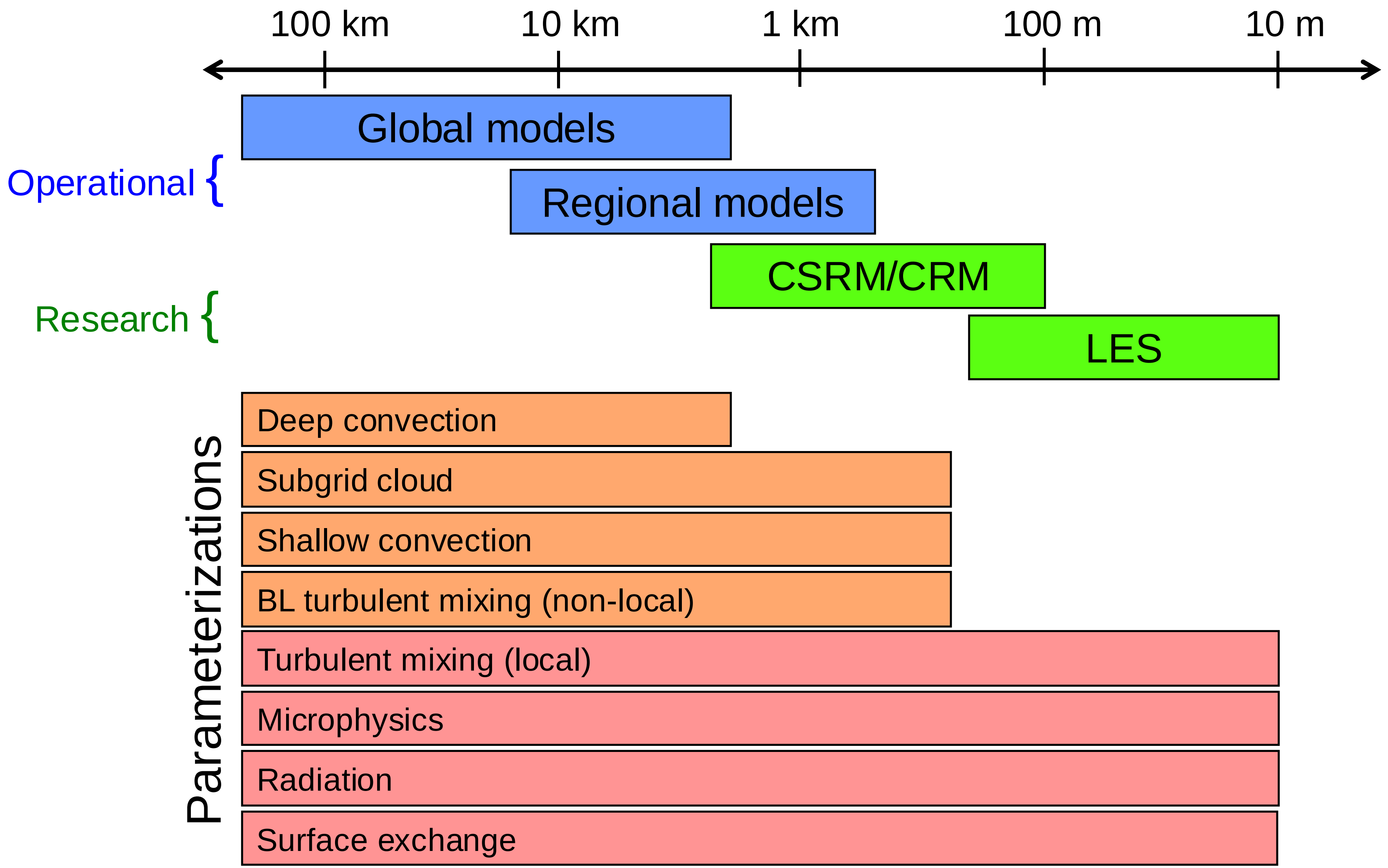


Map of the cloud size for which 50% of cloud cover comes from larger clouds (from 2 years of MODIS data)

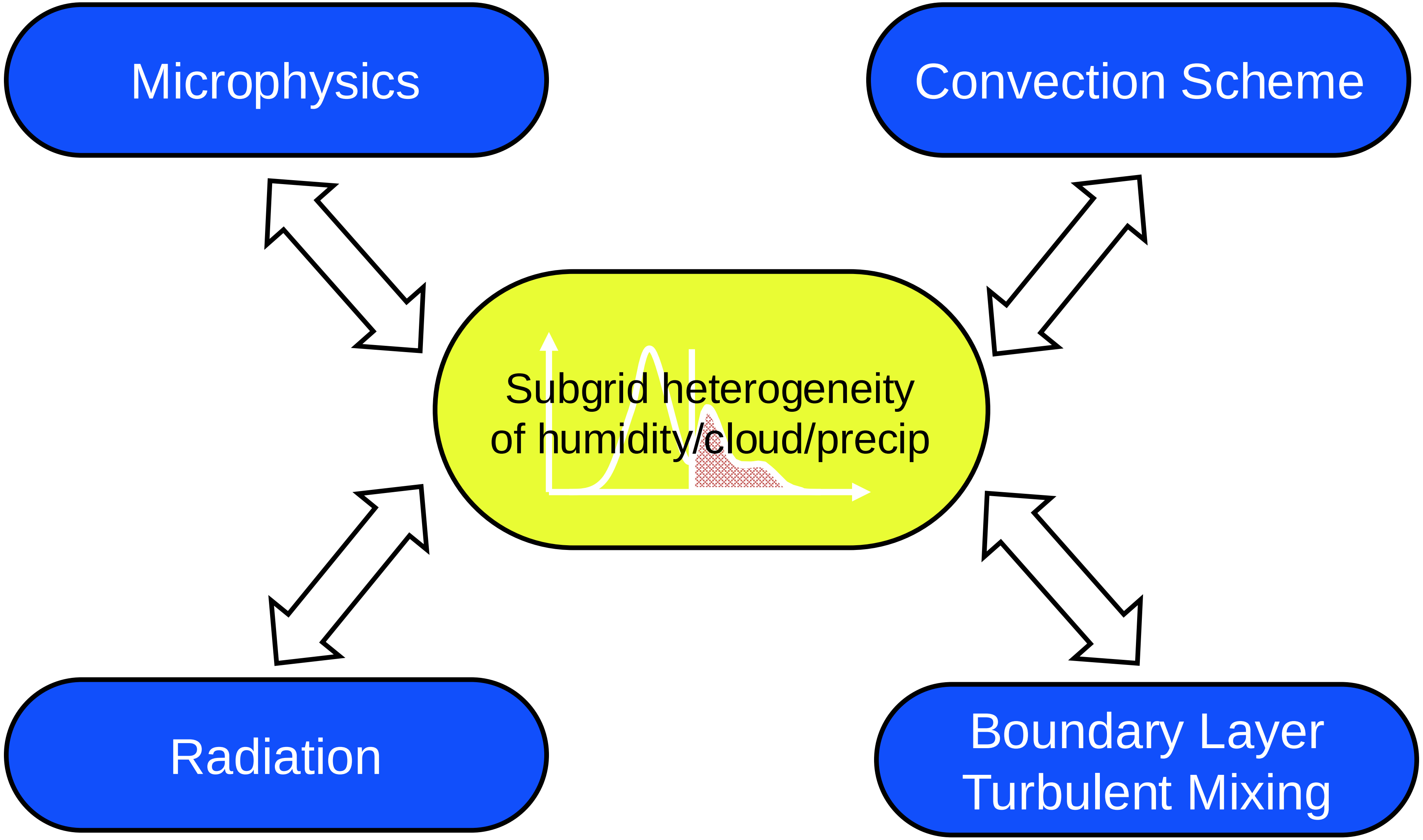


- 15% of global cloud cover comes from clouds smaller than 10 km
  → smaller scales still important, particularly dominate over subtropical oceans
- 85% of global cloud cover comes from clouds larger than 10km
  → condensate heterogeneity more important than cloud cover?

Scales of heterogeneity: Model parametrizations



Scales of heterogeneity: Consistency across model parametrizations



(1) Scales of heterogeneity: Summary

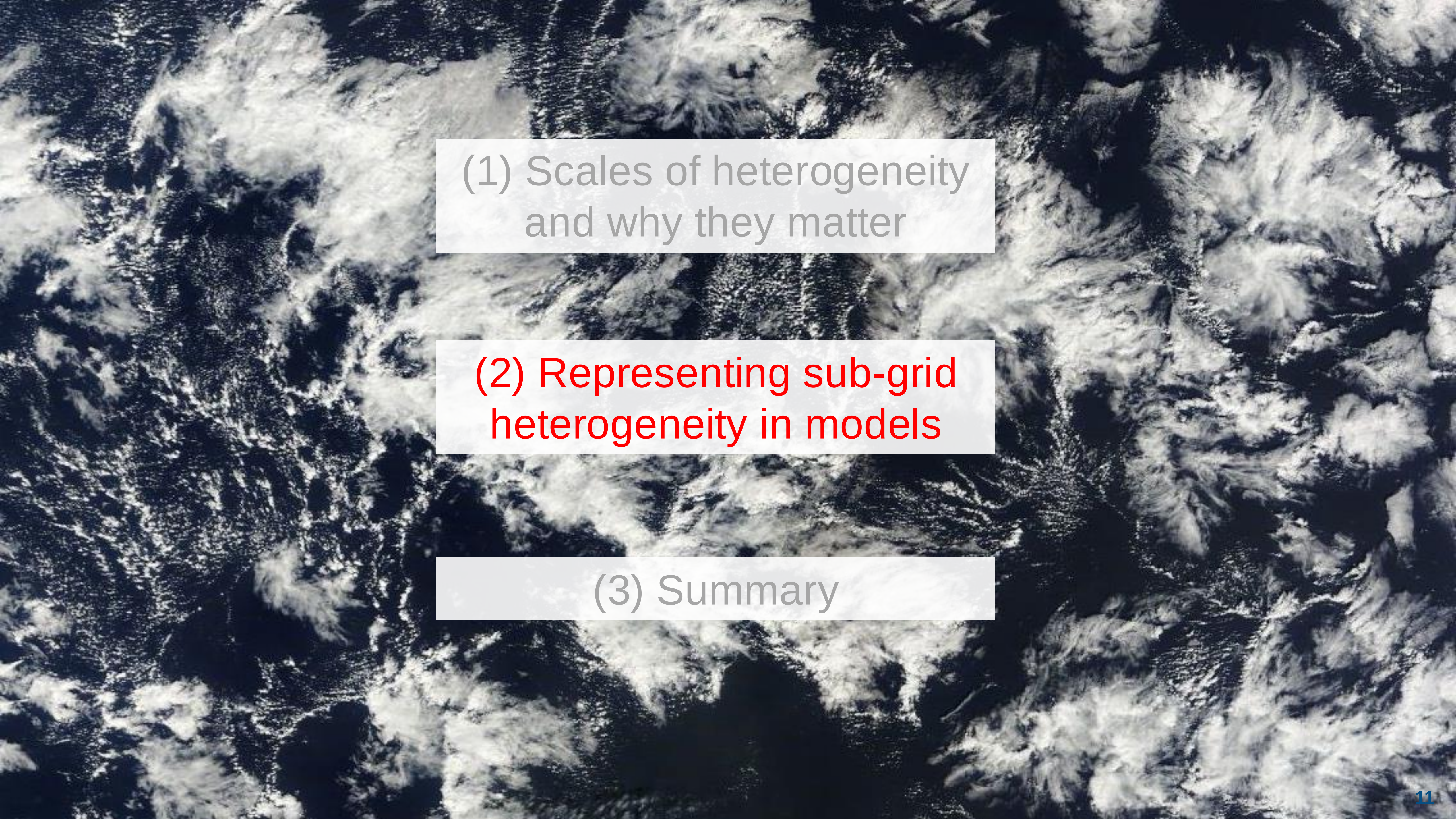
Sub-grid heterogeneity of cloud:

1. Humidity, cloud ←→ subgrid turbulence/convection

2. Important for radiation, precipitation, latent heating

3. Less important with increasing model resolution, but still relevant < 10km

4. Aim for a consistent representation across model parametrizations



(1) Scales of heterogeneity and why they matter

(2) Representing sub-grid heterogeneity in models

(3) Summary

Representing subgrid heterogeneity in a cloud scheme

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)

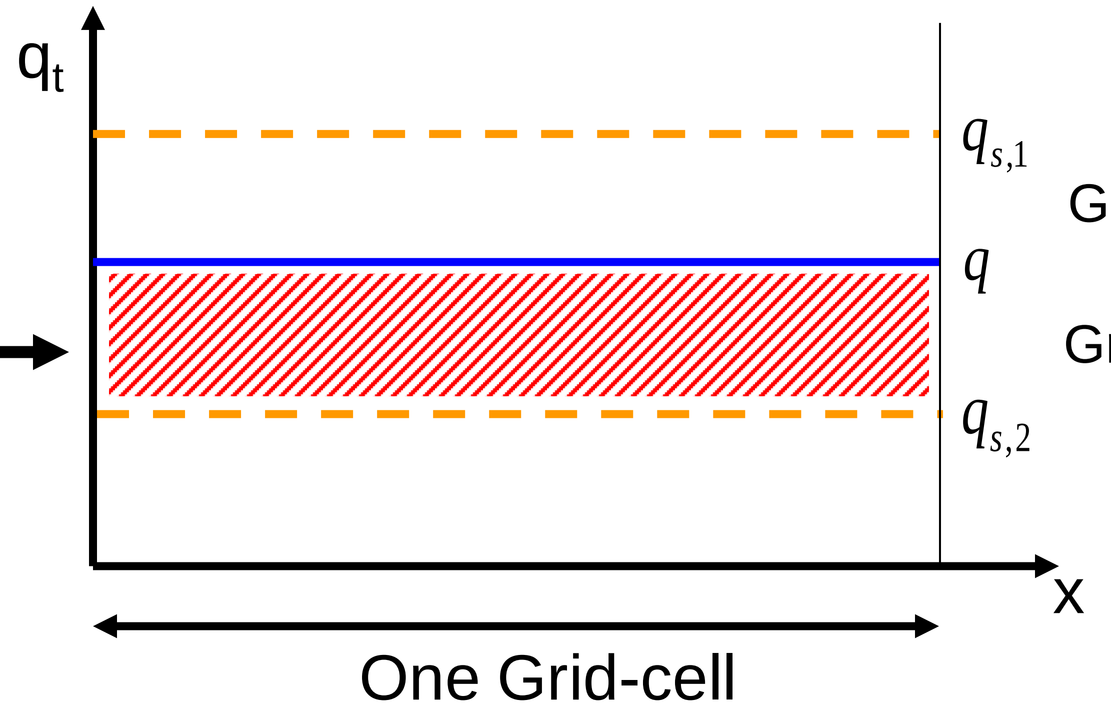
$$q_v = q_s \qquad q_c = q_t - q_s$$

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

Representing subgrid heterogeneity in a cloud scheme

Homogeneous distribution of water vapour and temperature:

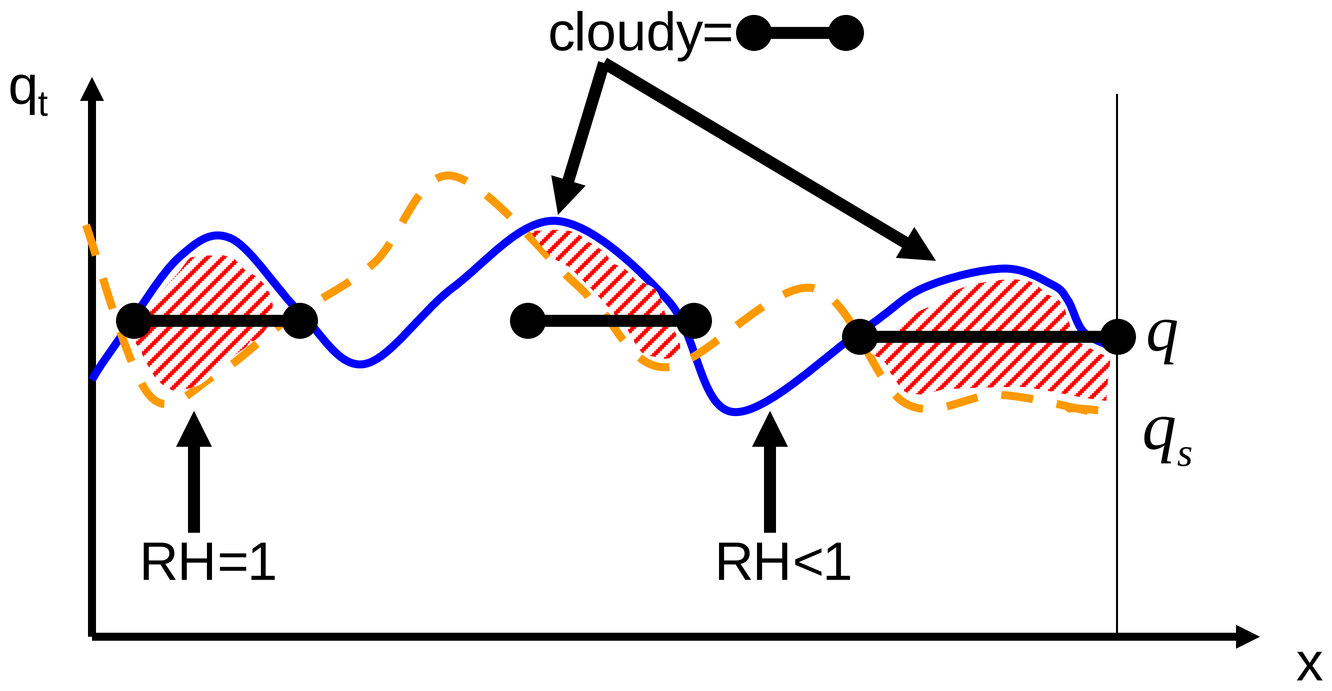
Note in the second case the relative humidity=1 from our assumptions



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

Representing subgrid heterogeneity in a cloud scheme

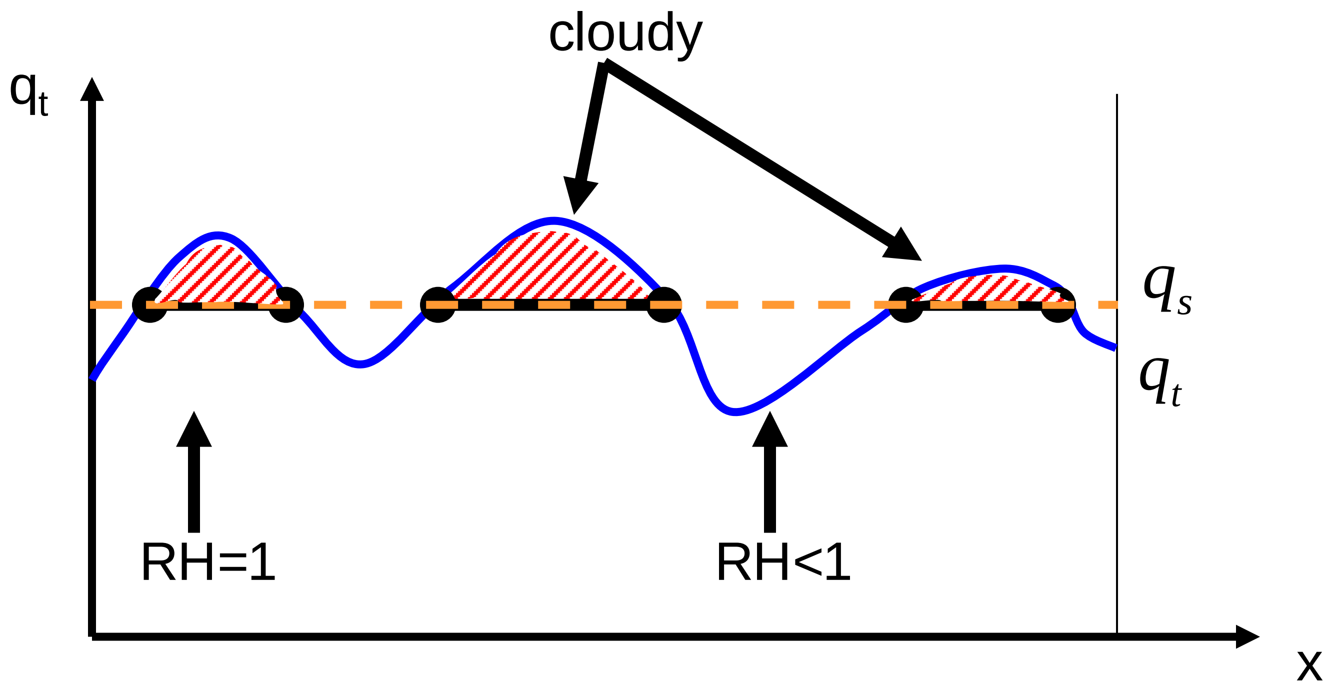
Heterogeneous distribution of *T* and *q*



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

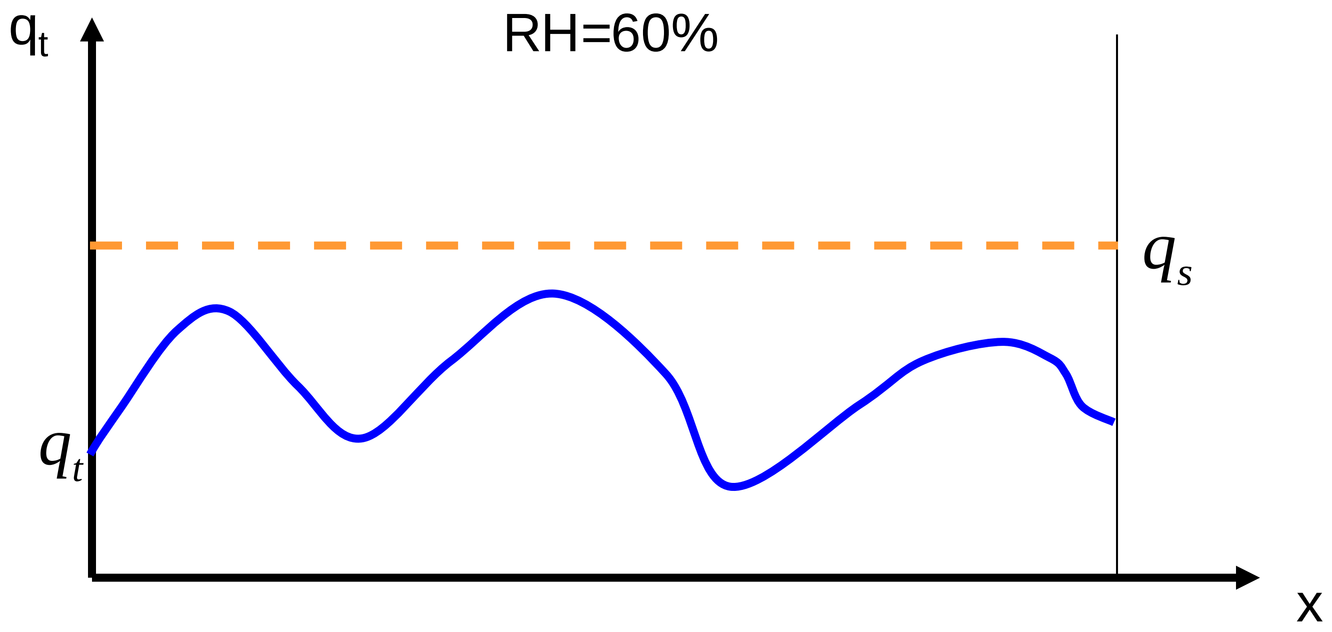
Representing subgrid heterogeneity in a cloud scheme

Heterogeneous distribution of *q only*



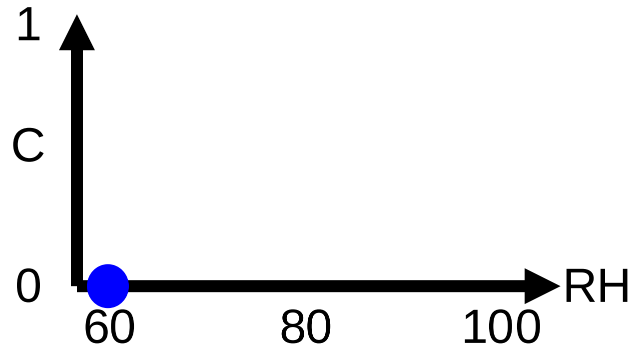
- The interpretation does not change much if we only consider humidity variability and assume uniform temperature (and therefore uniform saturation humidity = f(T,p)
- Analysis of observations and model data indicates humidity fluctuations are more important *most* of the time.

Simple Diagnostic Cloud Schemes: Relative Humidity Scheme



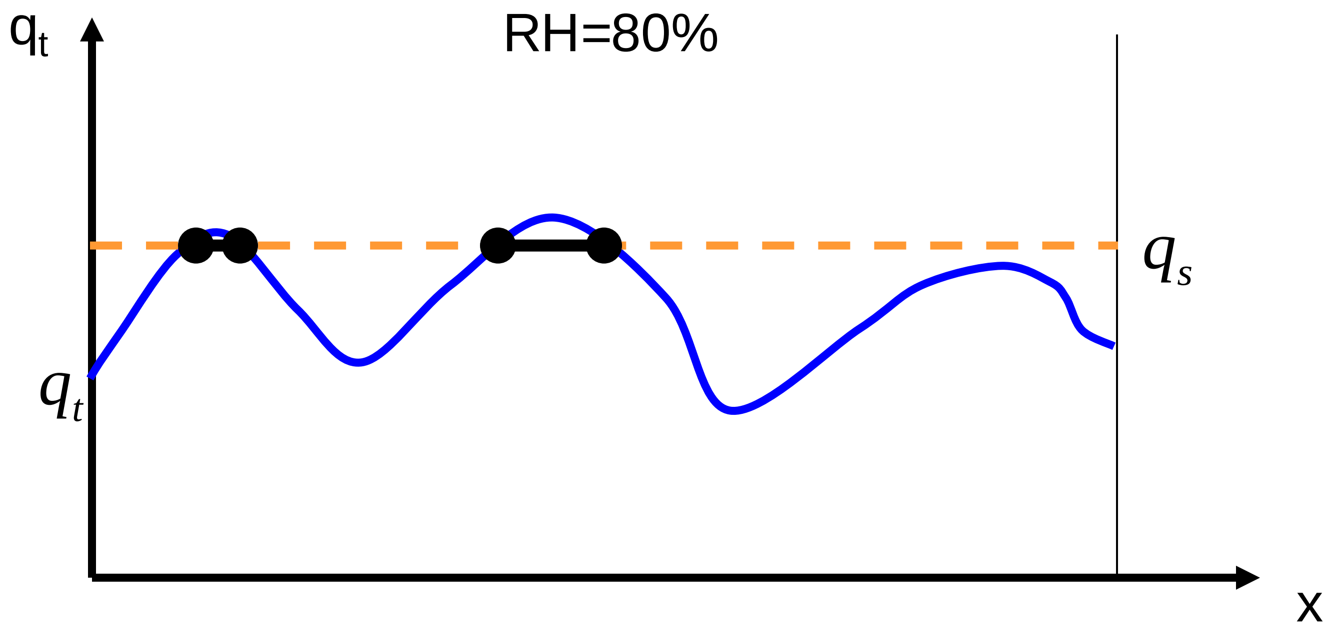
Take a grid cell with a certain (fixed) distribution of total water.

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

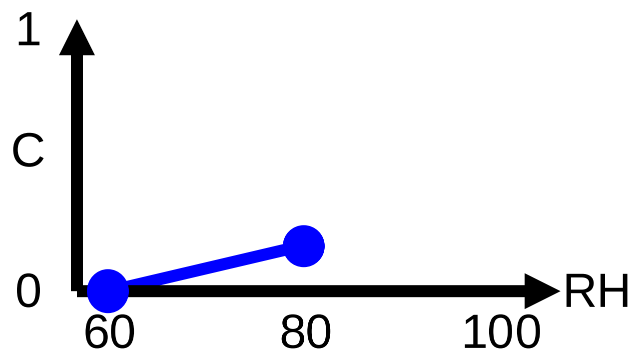


Representing subgrid heterogeneity in a cloud scheme

Simple Diagnostic Cloud Schemes: Relative Humidity Scheme

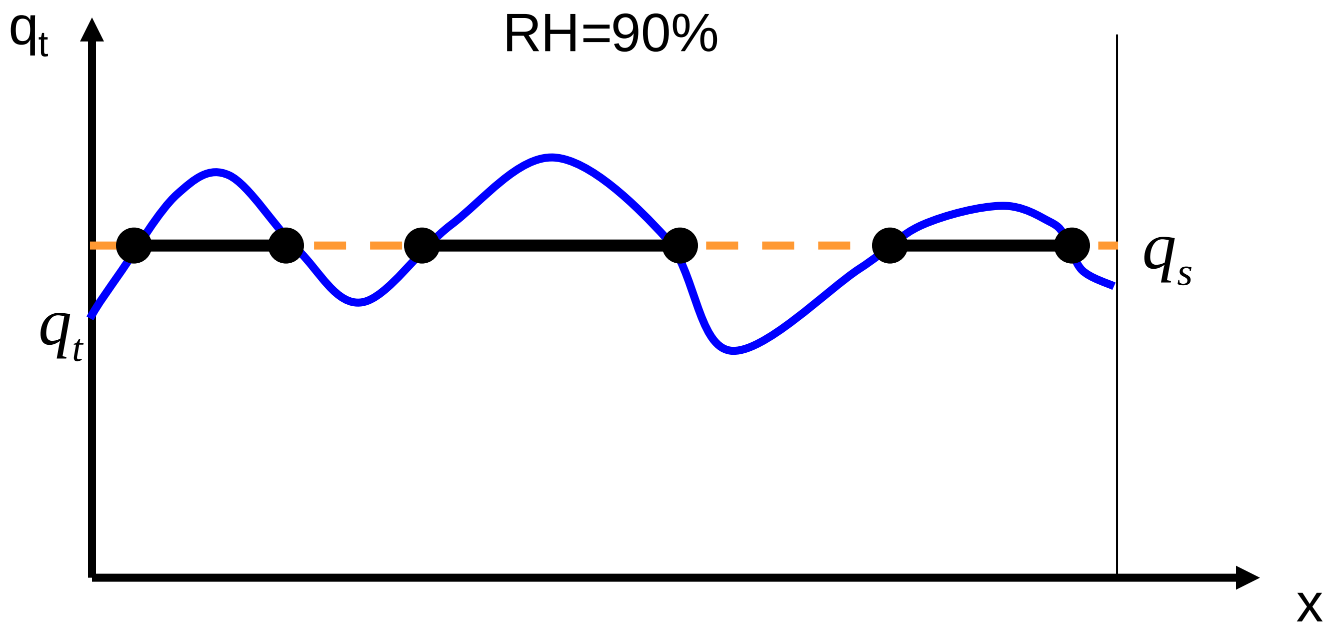


Add water vapour to the gridcell, the moistest part of the cell become saturated and cloud forms. The cloud cover is low.

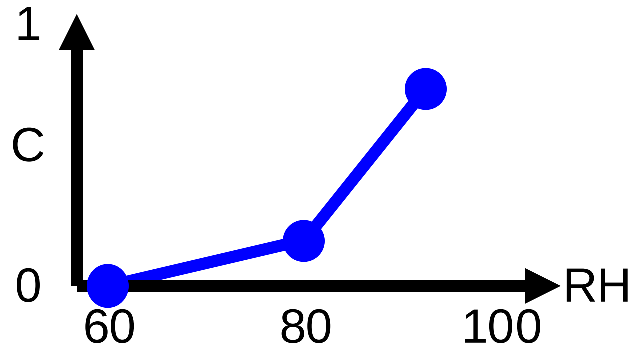


Representing subgrid heterogeneity in a cloud scheme

Simple Diagnostic Cloud Schemes: Relative Humidity Scheme

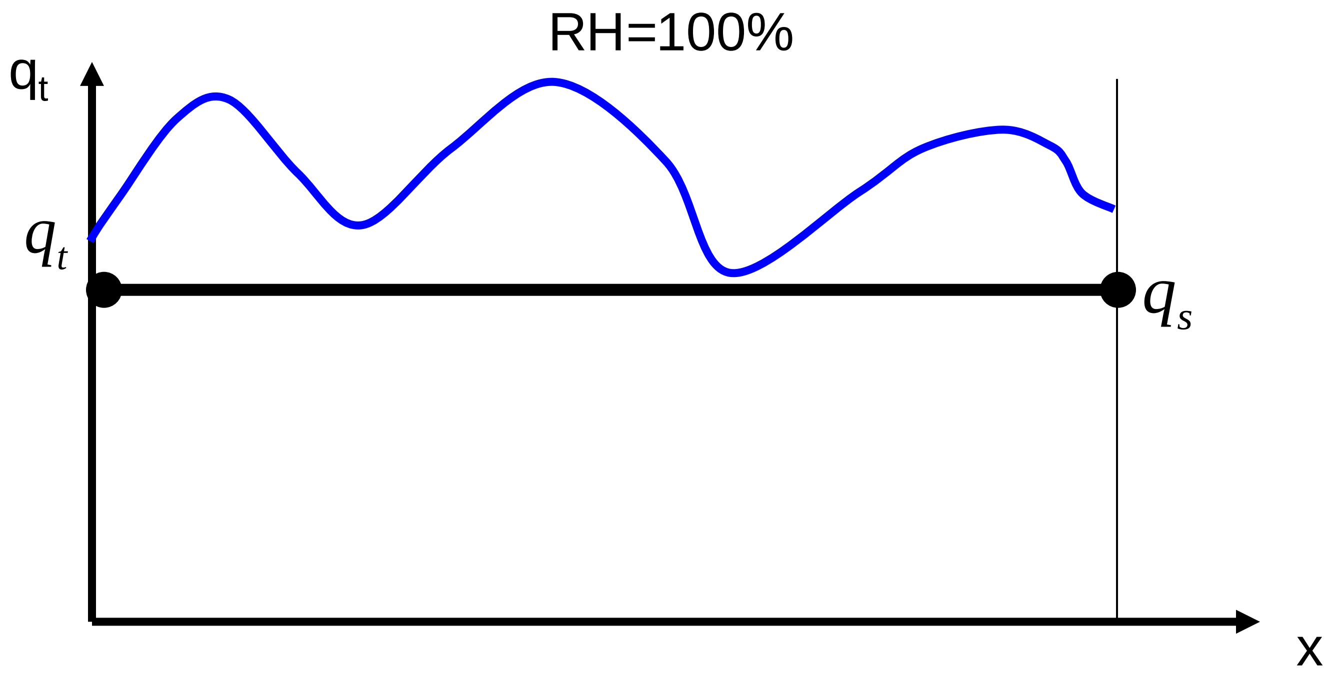


Further increases in RH
increase the cloud cover



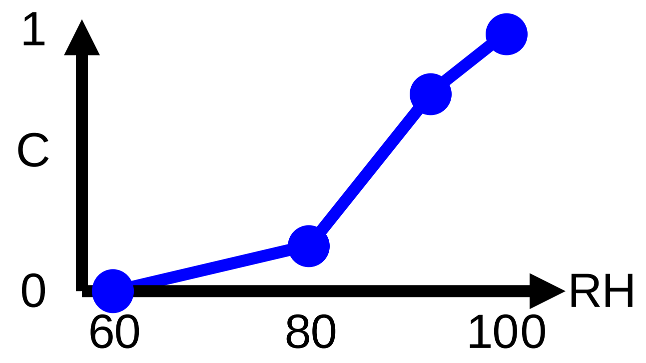
Representing subgrid heterogeneity in a cloud scheme

Simple Diagnostic Cloud Schemes: Relative Humidity Scheme



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

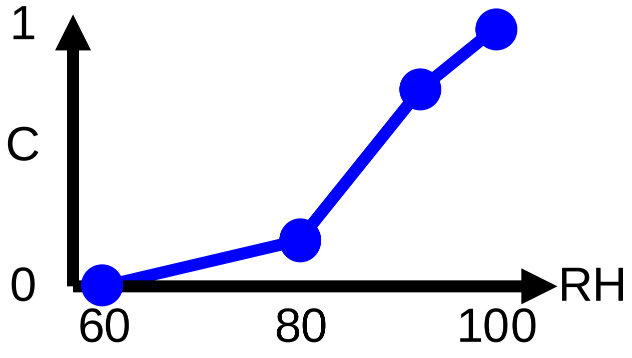
- Diagnostic RH-based parametrization C =f(RH)



Simple Diagnostic Cloud Schemes: Relative Humidity Scheme

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%)

Simple Diagnostic Cloud Schemes: Relative Humidity Scheme

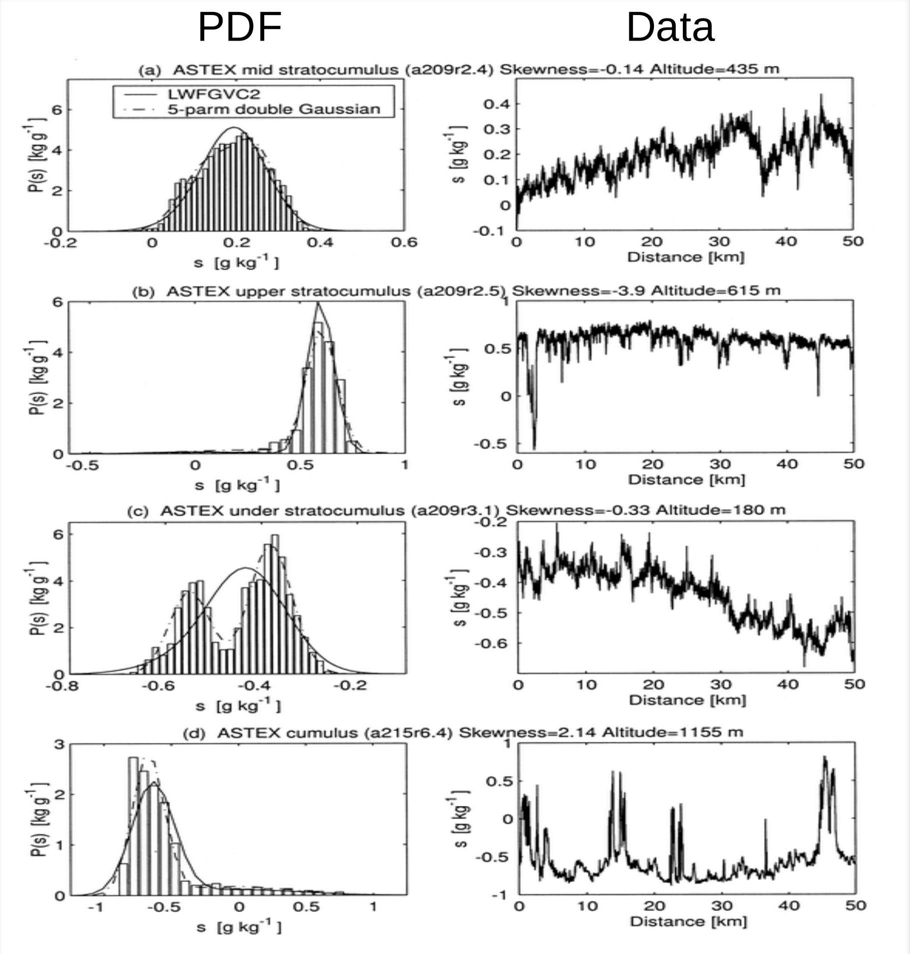
- Since these schemes form cloud when RH<100%, they implicitly assume subgrid-scale variability for total water, q_t, (and/or temperature, T).
- However, the actual PDF (the shape) for these quantities and their variance (width) are often not known.
- They are of the form: "*Given a RH of X% in nature, the mean distribution of q_t is such that, on average, we expect a cloud cover of Y%*".
- Ideally, we would like to represent the full PDFs (for humidity, temperature, condensate, vertical velocity etc) and how they vary in space and time…

Representing sub-grid heterogeneity: Observed PDF of total water

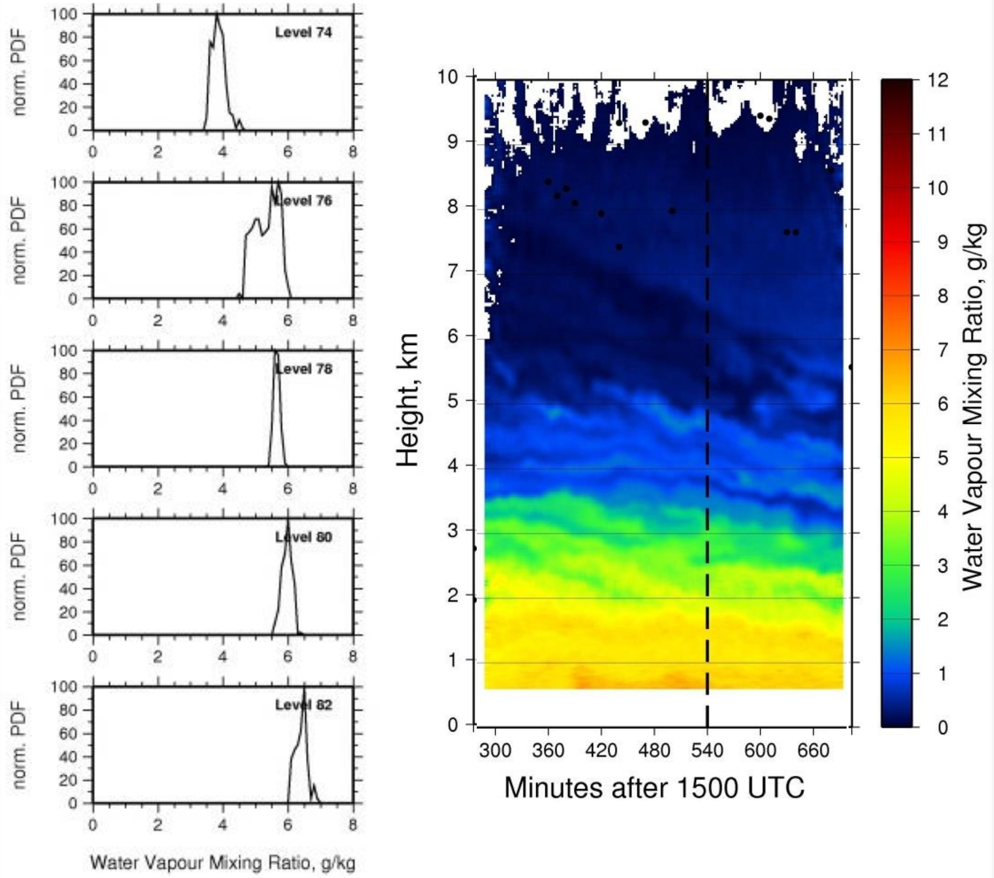
Observations from aircraft, tethered balloon, satellite, Raman lidar

…and LES model data…

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

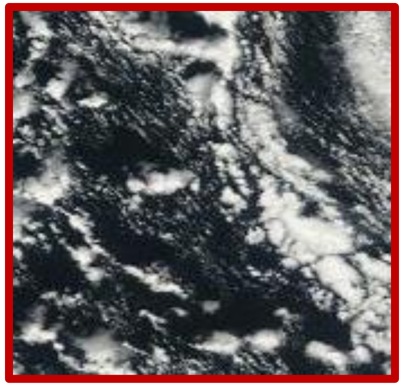


Observations from aircraft (Larson et al. 2001)



Raman lidar 15/16 May 2008 (from Franz Berger)

Representing sub-grid heterogeneity: PDF of total water – statistical schemes



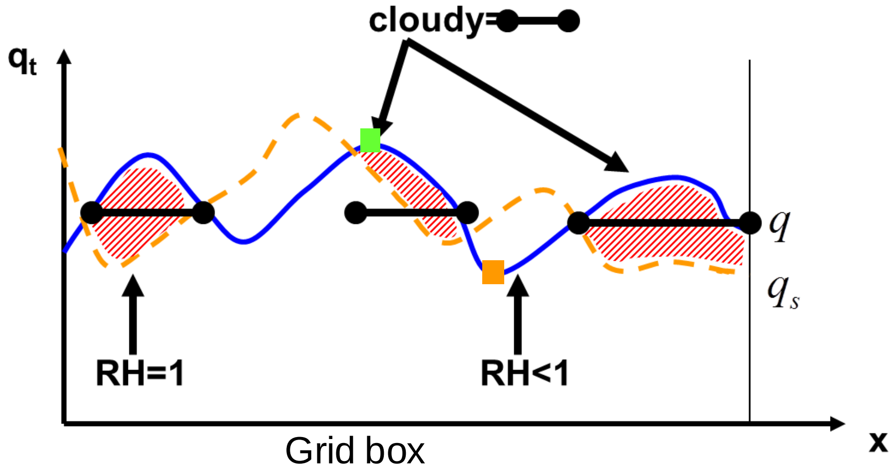
Statistical schemes explicitly specify the probability density function (PDF), G, for quantity, s, (or total water q_t if assume T homogeneous) (Sommeria and Deardorff 1977; Mellor 1977)

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

$$a_L = \left[1 + \frac{L}{C_p}\alpha_L\right]^{-1} \qquad \alpha_L = \frac{\partial q_s}{\partial T}\left(\overline{T}_L\right)$$

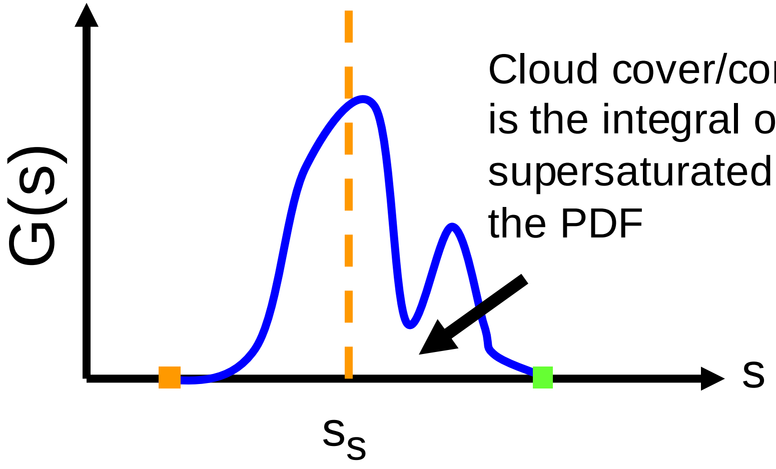
Liquid water temperature

$$T_L = T - \frac{L}{C_p} q_L$$



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

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



Cloud cover/condensate is the integral of the supersaturated part of the PDF

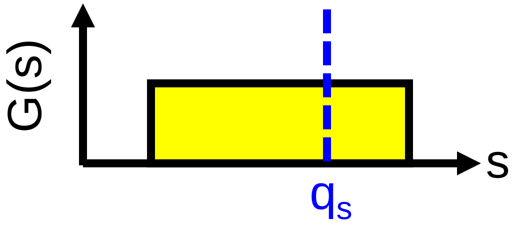
Representing sub-grid heterogeneity: Modelled PDF of total water

Represent with a functional form, specify the:

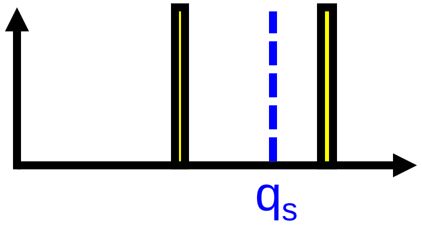
(1) PDF type (delta, continuous, unimodal, bimodal, symmetrical, bounded?)

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

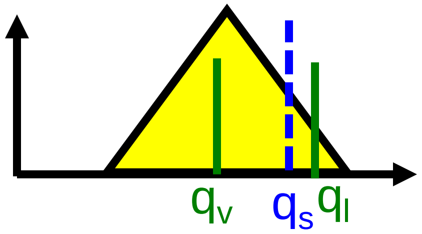
(3) Diagnostic or prognostic (how many degrees of freedom?)



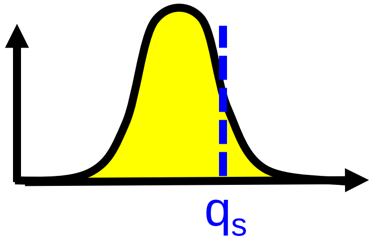
Uniform:
Sundquist (1978)
Letreut and Li (1991)



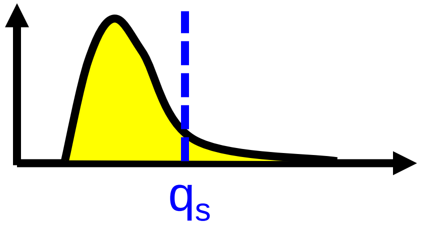
Double Delta Fn:
Randall et al. (1992)
Lappen and Randall (2001)



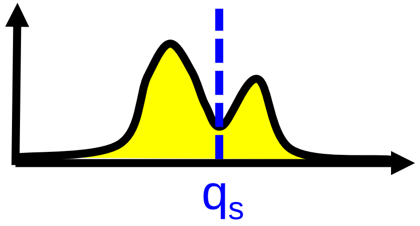
Triangular:
Smith (1990)



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



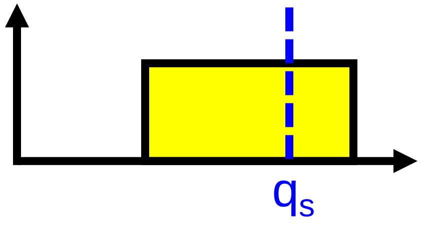
Gamma/Lognormal/Beta:
Bougeault (1982)
Barker et al. (1996)
Tompkins (2002)



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

Diagnostic statistical (RH) scheme: Sundquist (1989) – form used in many GCMs

(1) Uniform PDF
(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

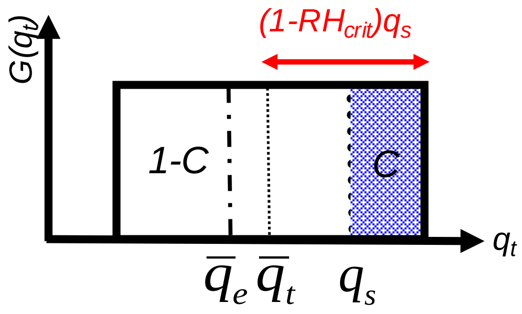
Other schemes:
- Smith (1990) Met Office LAMs triangular distribution
- Xu and Randall (1996) extended to C=fn(RH,qc)

If PDF moments are fixed (i.e. in this case width of the "top-hat" function), then equivalent to a diagnostic "relative humidity" scheme:

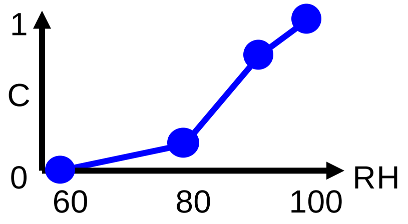
$$\bar{q}_v = Cq_s + (1-C)\bar{q}_e$$

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

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

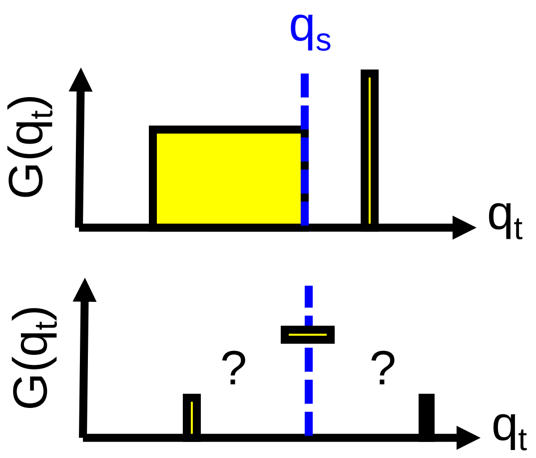


$$C = 1 - \sqrt{\frac{1-RH}{1-RH_{crit}}}$$



Prognostic cloud fraction scheme: Tiedtke (1993) ECMWF operational since 1995

(1) Uniform/delta function
(2) Prognostic: humidity, condensate, 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

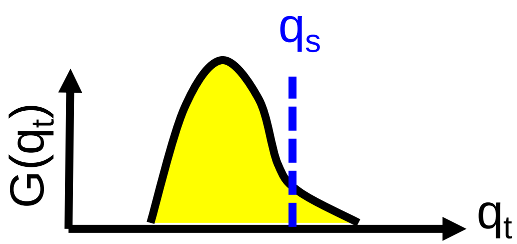
Other schemes:
- PC2 Met Office global (Wilson et al. 2008)

Prognostic PDF scheme: Tompkins (2002) ECHAM

(1) Bounded Beta function with positive skewness

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

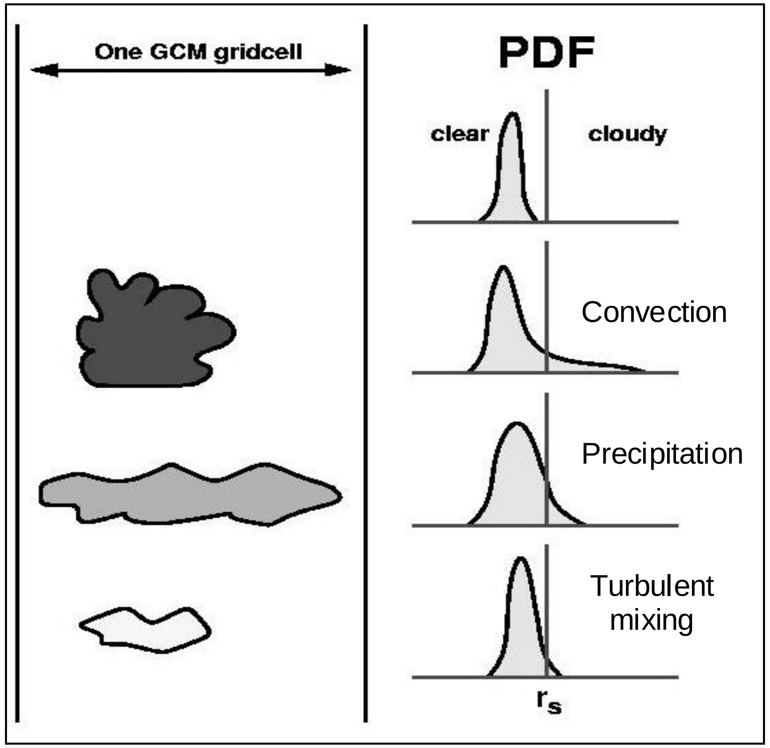
(3) ~3 degrees of freedom + convection



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)



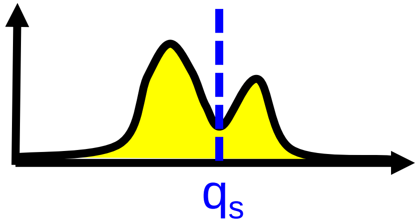
Prognostic PDF high order closure scheme: Golaz et al. (2002), CLUBB

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

(2) Prognostic: w, θ_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 predicted vertical velocity (w) for aerosol activation?
- Tested in WRF, CAM (Bogenschutz et al. 2013), GFDL (Guo et al. 2014)

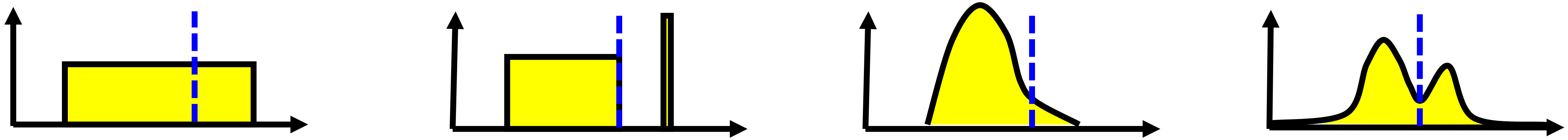
Disadvantages:

- Computationally more 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

Representing sub-grid heterogeneity: Key characteristics for the PDF?



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

- 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.

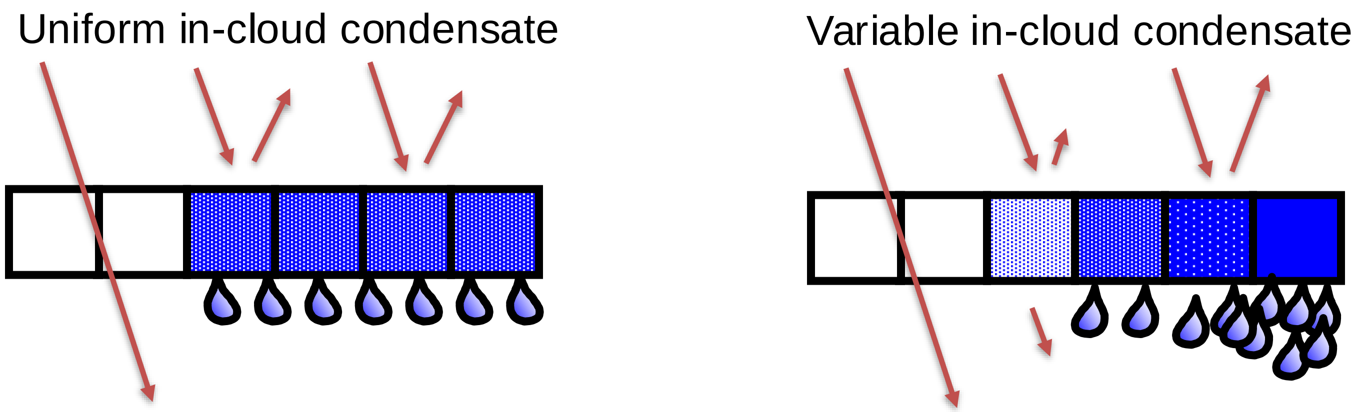
- Many different schemes are used in NWP/climate models, but the most important characteristics of a scheme are:

1. To represent sub-grid cloud fraction – if q or $q_s(T)$ changes, how does this affect cloud fraction/condensate
2. To represent subgrid heterogeneity of condensate – for unbiased radiation, microphysics
3. Enough degrees of freedom to represent the main variations in different cloud regimes – mean, variance and skewness (skewed PDF for convection – can have low grid-box mean humidity, but convective clouds in part of the gridbox)

Representing in-cloud sub-grid heterogeneity of cloud/precipitation

Representation of subgrid heterogeneity of cloud (and precipitation) important for radiation and microphysics:

- Radiation – non-linear impact of cloud optical thickness
- Microphysics – non-linear impact on autoconversion, and accretion (covariance of cloud and rain)



A simple measure of the variability that can be used as a modification to the radiation optical depth and autoconversion/accretion calculations is the fractional standard deviation of the condensate PDF (the standard deviation divided by the mean) which can be derived from observations:

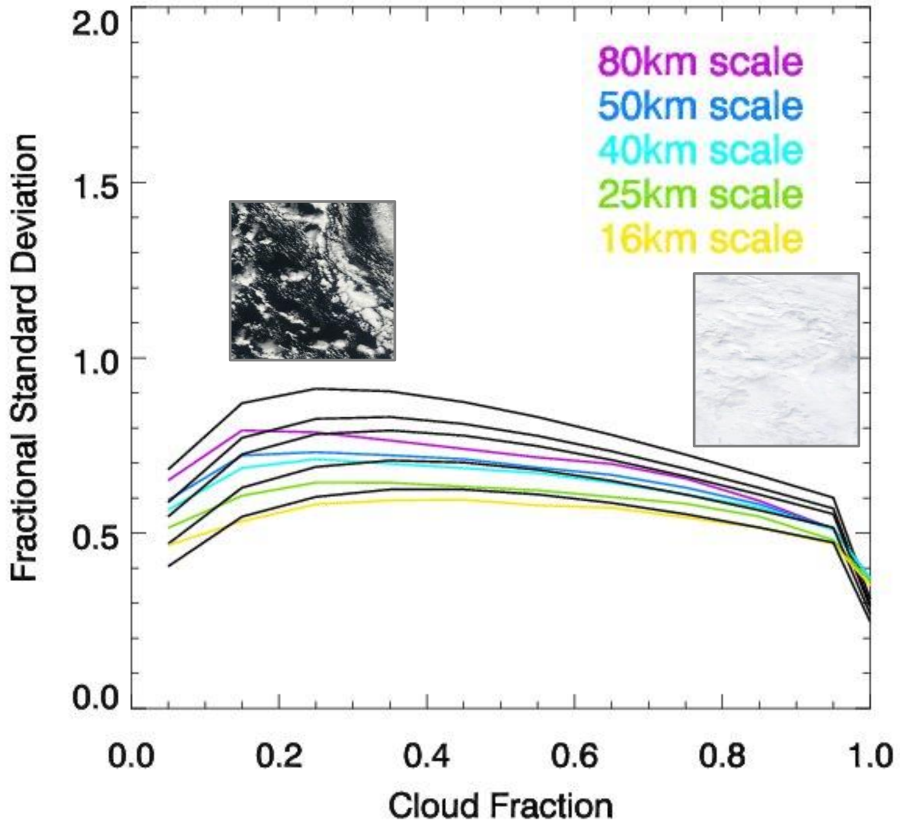
$$FSD_c = stdev(q_c) \,/\, mean(q_c)$$

Representing in-cloud sub-grid heterogeneity of cloud/precipitation

Parametrizing fractional standard deviation of condensate

$$FSD_c = stdev(q_c) / mean(q_c)$$

FSDc Azores



e.g. Boutle et al. (2014), Ahlgrimm and Forbes (2016)

Parameterize as a function of cloud fraction and scale length.

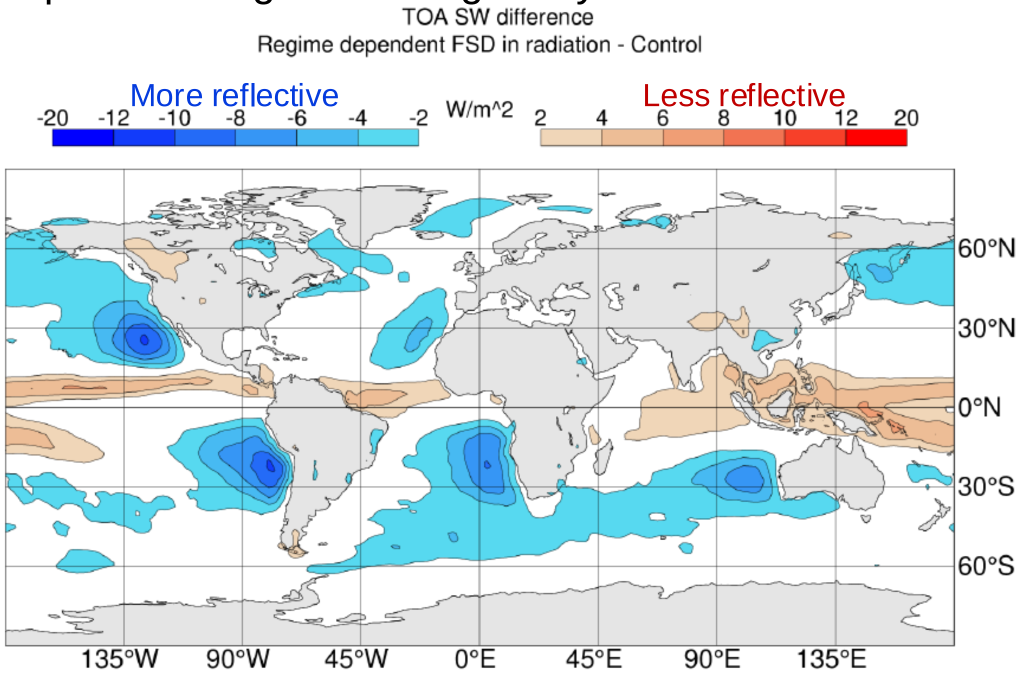
Captures the observed variation of FSD at multiple sites, different regimes

Use for radiation (McICA) and microphysics

Representing in-cloud sub-grid heterogeneity of cloud/precipitation

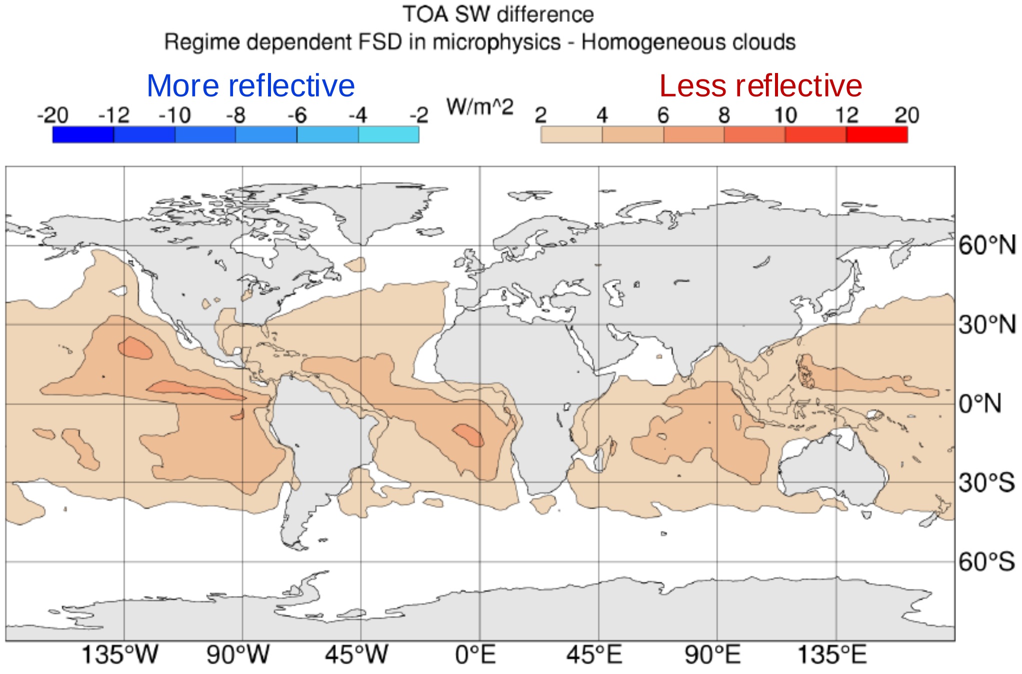
Impact of representing subgrid heterogeneity of cloud liquid water on top-of-atmosphere shortwave radiation (IFS model climate)

Impact of subgrid-heterogeneity in radiation scheme

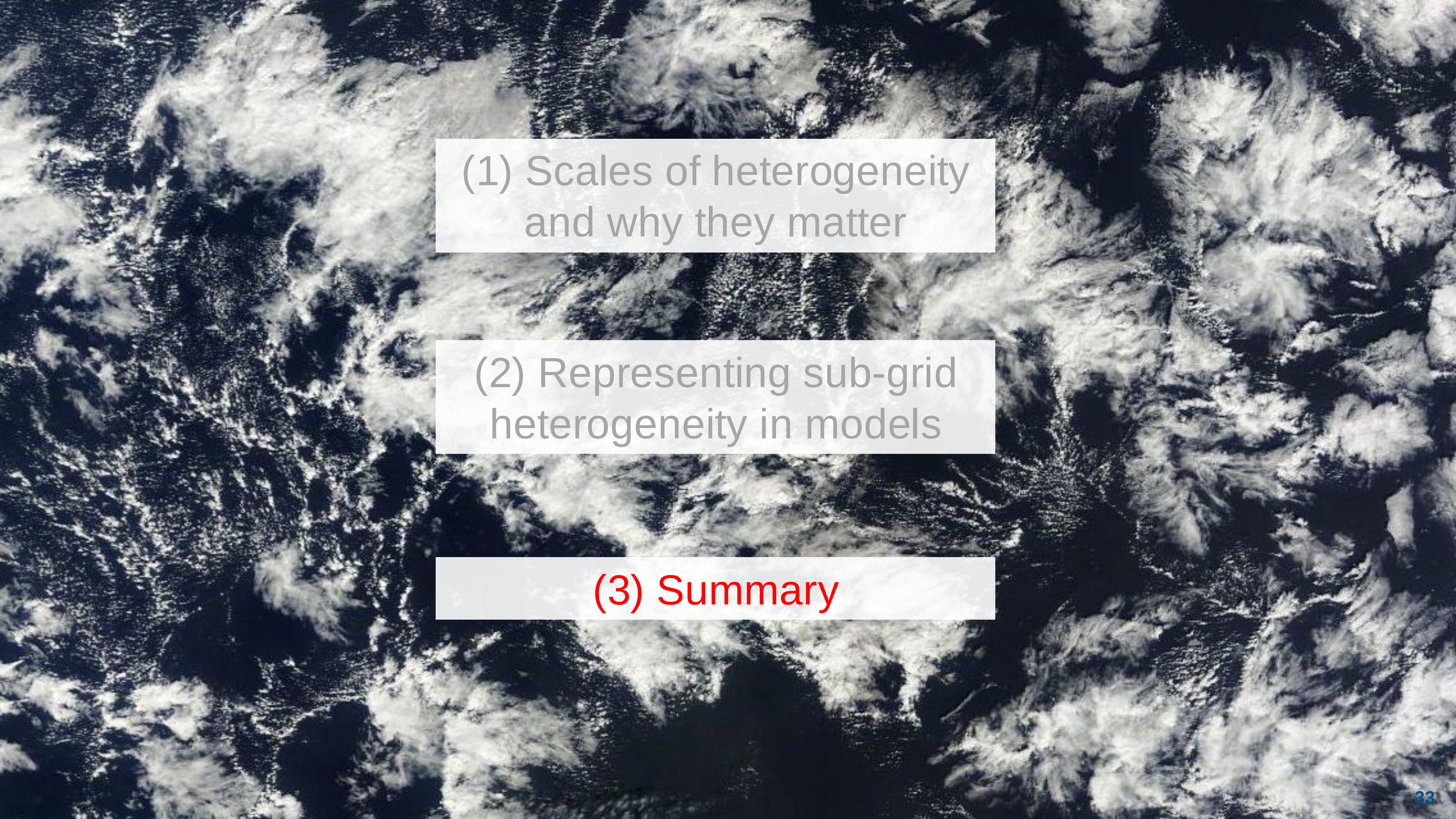


Stratocumulus cloud (high cloud fraction) more uniform reflective than standard FSD=0.7 and less reflective in highly heterogeneous tropical deep convection along ITCZ

Impact of subgrid-heterogeneity in microphysics scheme



Autoconversion and accretion rates higher when include heterogeneity, so less cloud water and less reflection of SW radiation



(1) Scales of heterogeneity and why they matter

(2) Representing sub-grid heterogeneity in models

(3) Summary

Summary: Representing subgrid scale heterogeneity

- Representing sub-gridscale heterogeneity in GCMs is important for cloud formation, microphysical processes, radiation etc. (still required sub-10km, even at 1km)
- BL turbulence, shallow convection, deep convection, cloud scheme are all part of the sub-grid representation. Important to have consistency of assumptions between schemes.
- High order closure turbulence schemes unifying BL/Cu processes with assumed PDF work well for liquid-phase turbulent boundary layers, but not so straight forward to include subgrid ice phase, mixed-phase and precipitation, vertical overlap, or representing deep convection – ongoing research topics.
- More complex schemes with higher degrees of freedom allow greater flexibility to represent the real atmosphere, but we need to have enough knowledge/information to understand and constrain the assumptions in the schemes (globally in all meteorological regimes). Can simpler schemes be as effective in terms of their impacts?
- Conceptual framework important, but details matter! – specification of sources and sinks, numerical solutions...

Key driving concepts for the parametrization

- Fidelity – improved realism, physical basis
- Consistency – across parametrizations
- Convergence – across resolutions
- Complexity vs Cost vs Uncertainty
- Focus on impacts – radiative, thermodynamical, hydrological

Questions?