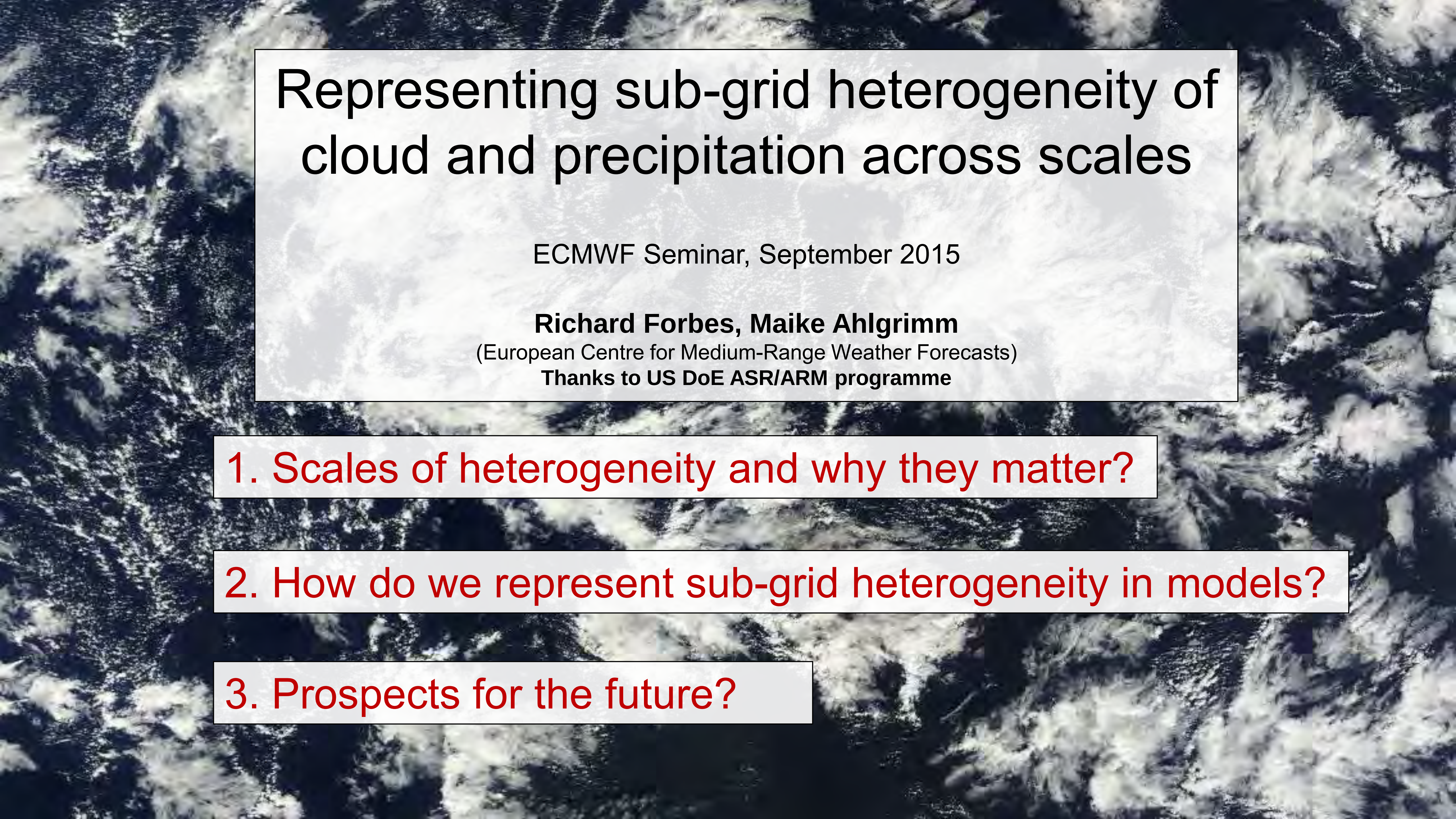


Representing sub-grid heterogeneity of cloud and precipitation across scales

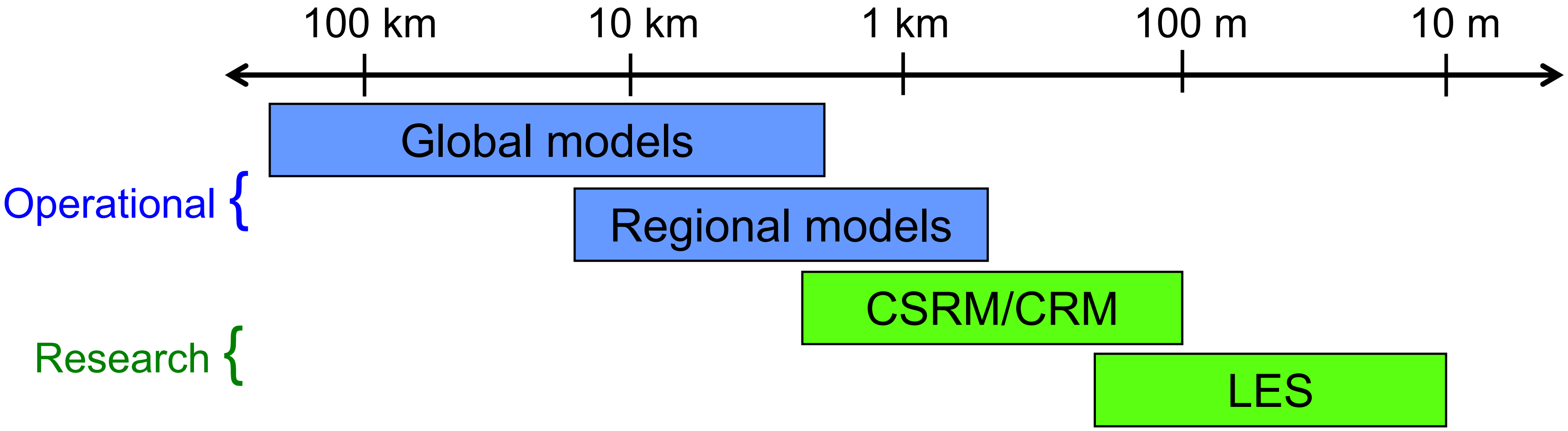
ECMWF Seminar, September 2015

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

Thanks to US DoE ASR/ARM programme

1. Scales of heterogeneity and why they matter?
2. How do we represent sub-grid heterogeneity in models?
3. Prospects for the future?

Scales of heterogeneity: Wide range of model resolutions



100 km

10 km

1 km

100 m

10 m

Operational {

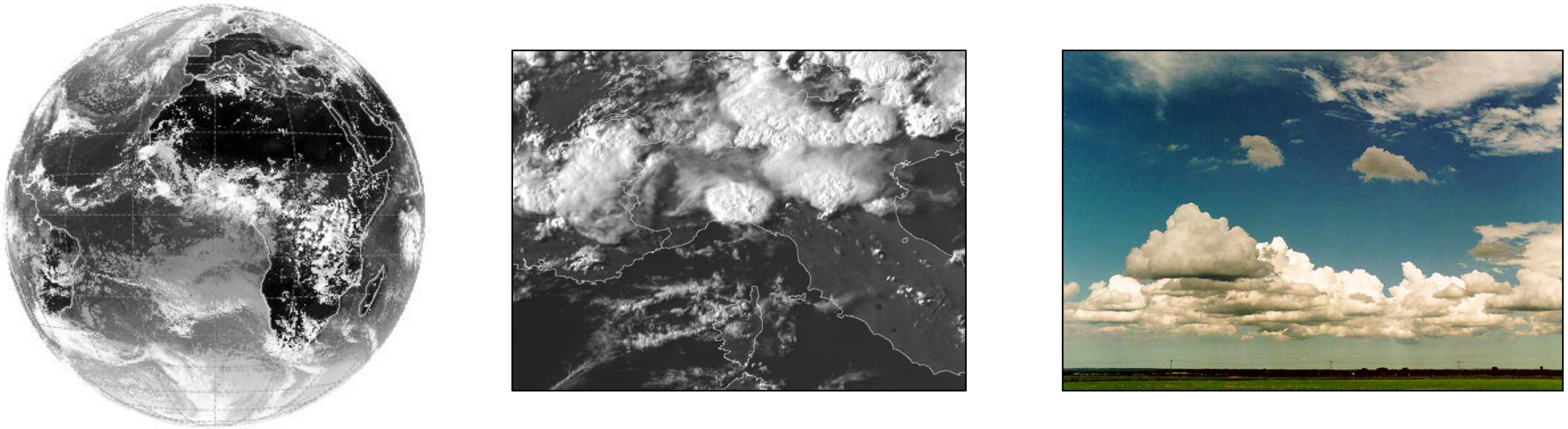
Global models

Regional models

Research {

CSRM/CRM

LES



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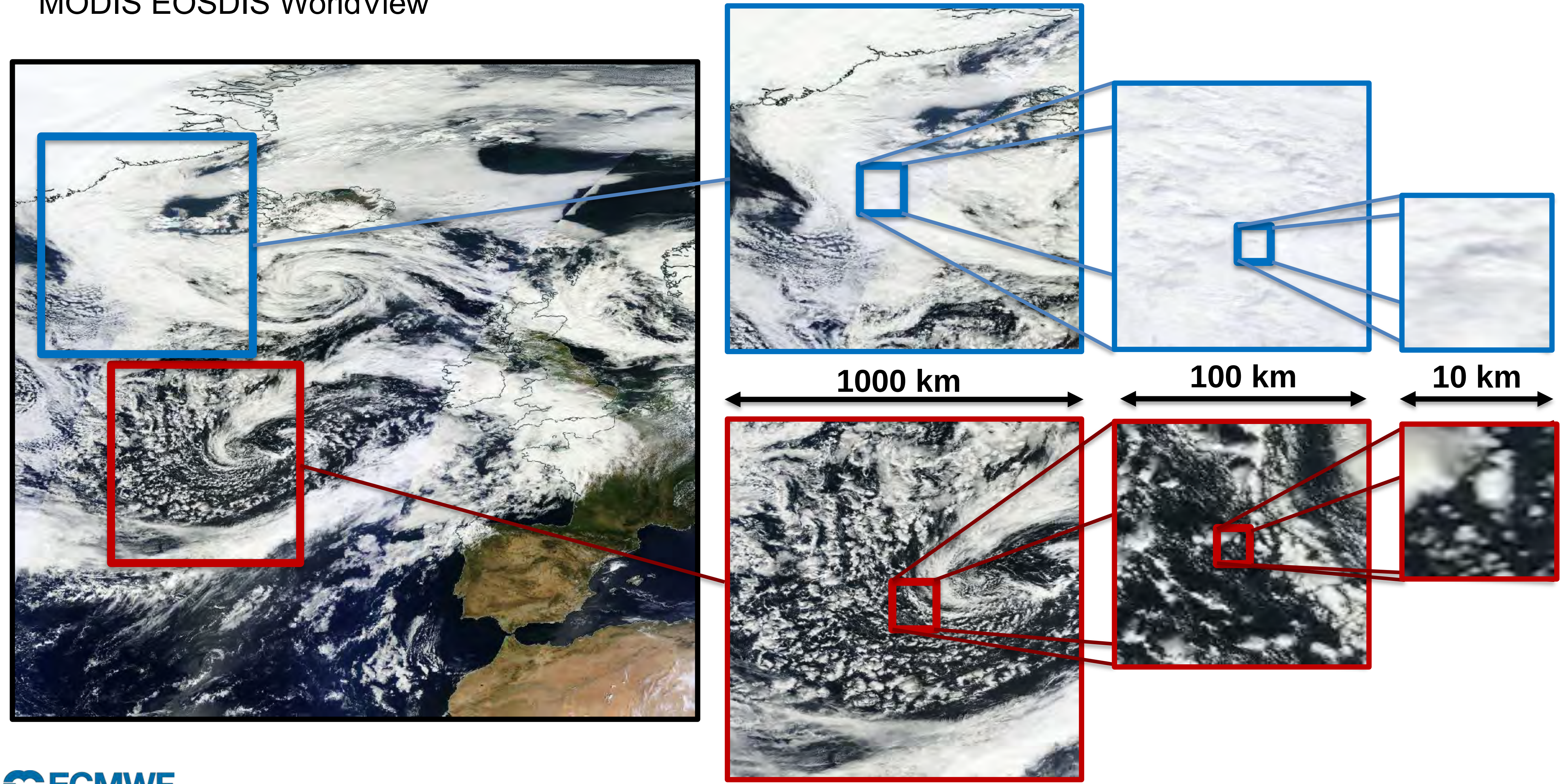
Scales of heterogeneity: Significant across scales



MODIS EOSDIS WorldView

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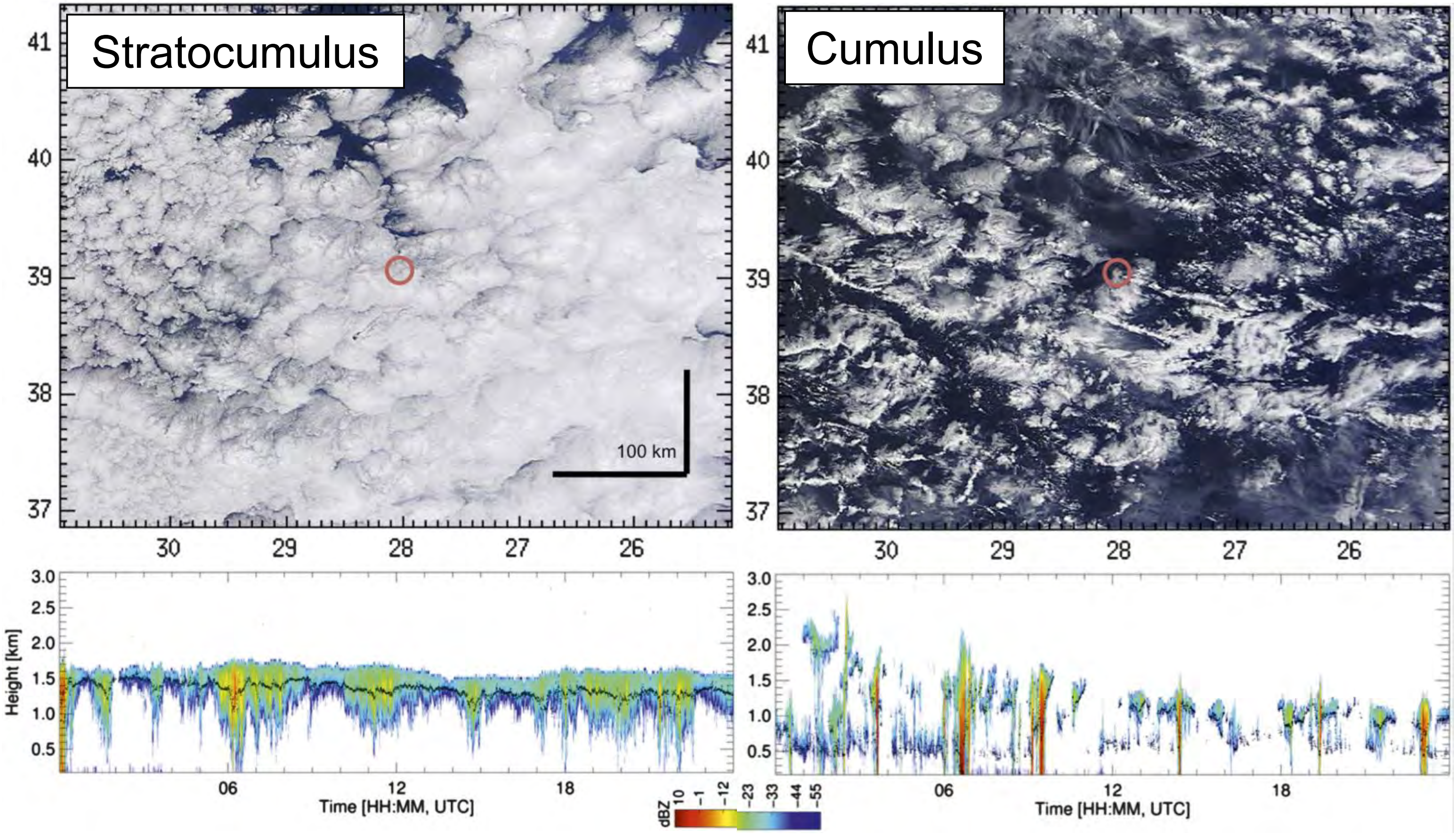
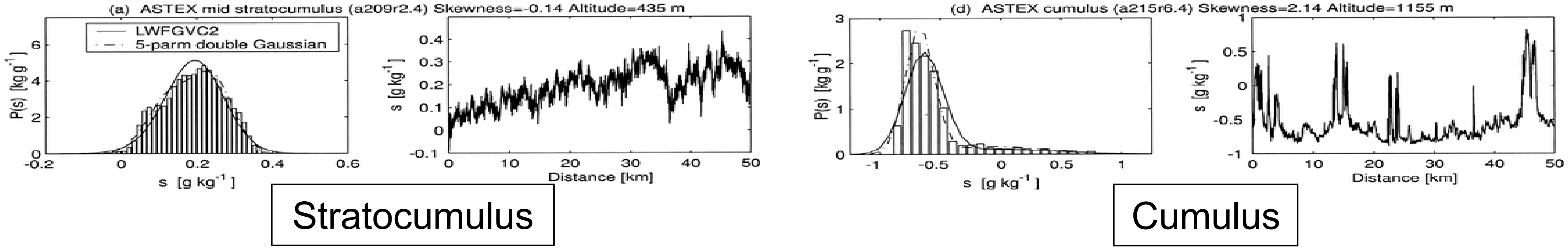
Scales of heterogeneity: Humidity, cloud and precipitation ←→ turbulence

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



ASTEX aircraft data
(Larson et al. 2001)



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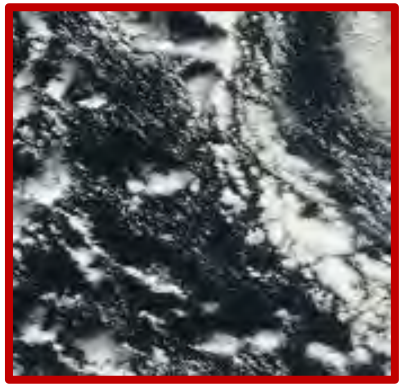
Scales of heterogeneity: Impacts on radiation, precipitation, latent heating

Subgrid heterogeneity of…

Vertical velocity

Humidity

Temperature



Precipitation

Cloud particle size

Cloud fraction

Cloud condensate

Cloud phase

Radiative Impacts

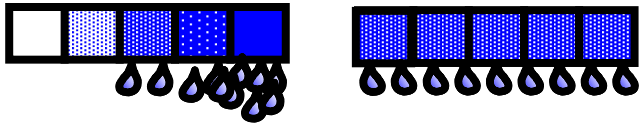
Cloudy sky versus clear sky fraction matters

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, uvw)

Chemistry in clouds

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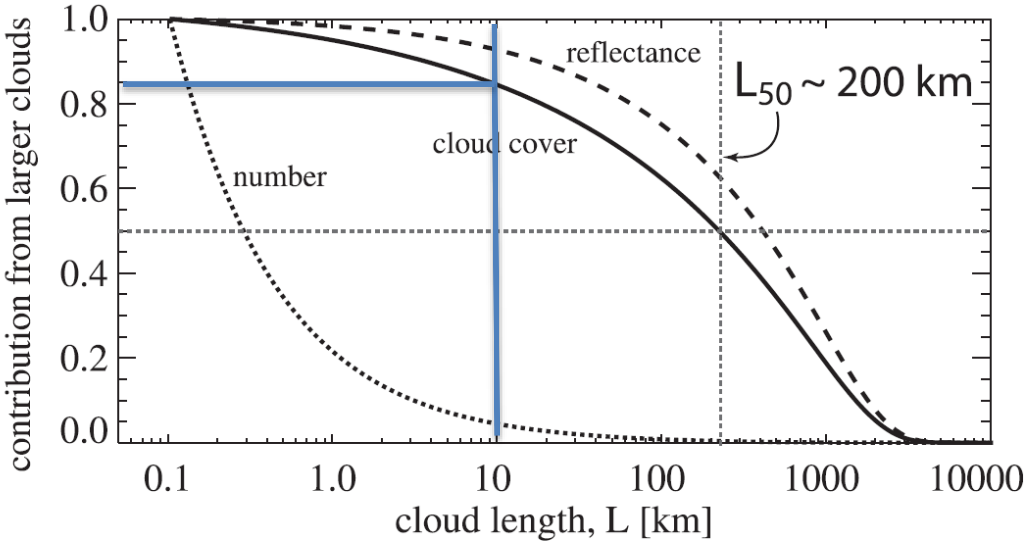
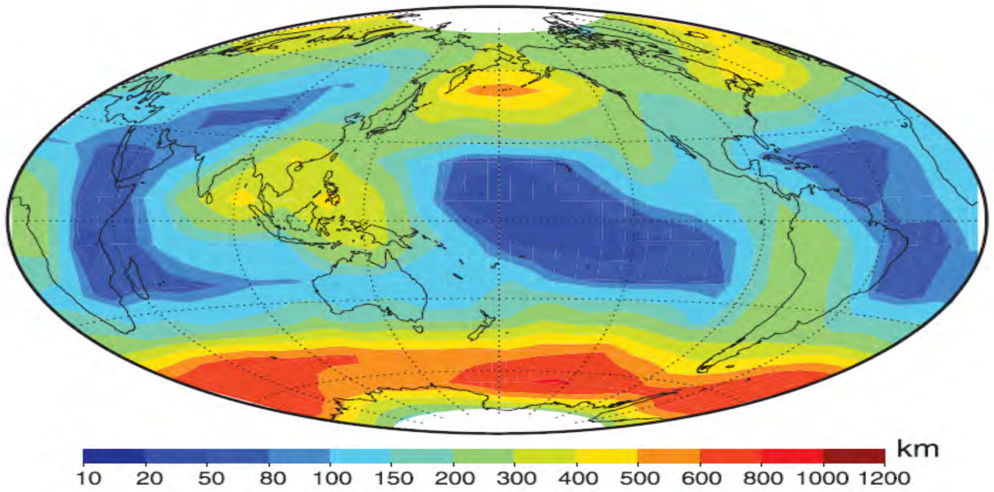
Scales of heterogeneity: Global cloud cover and reflectance

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?

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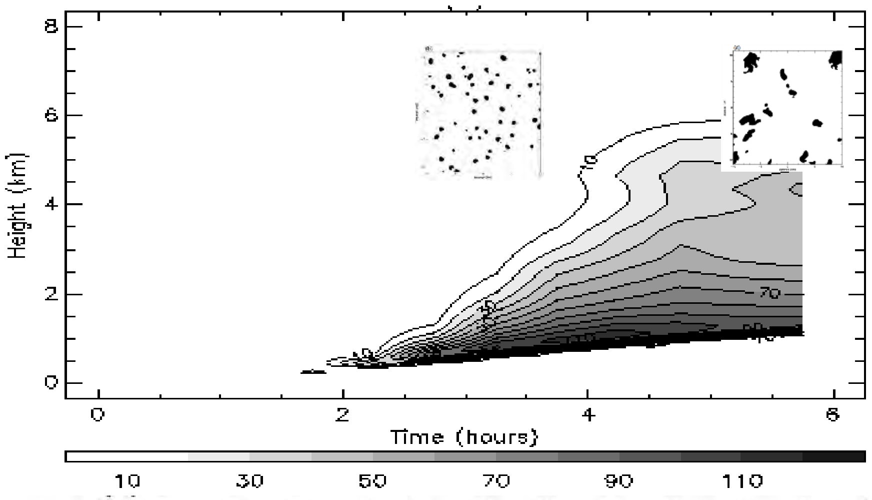
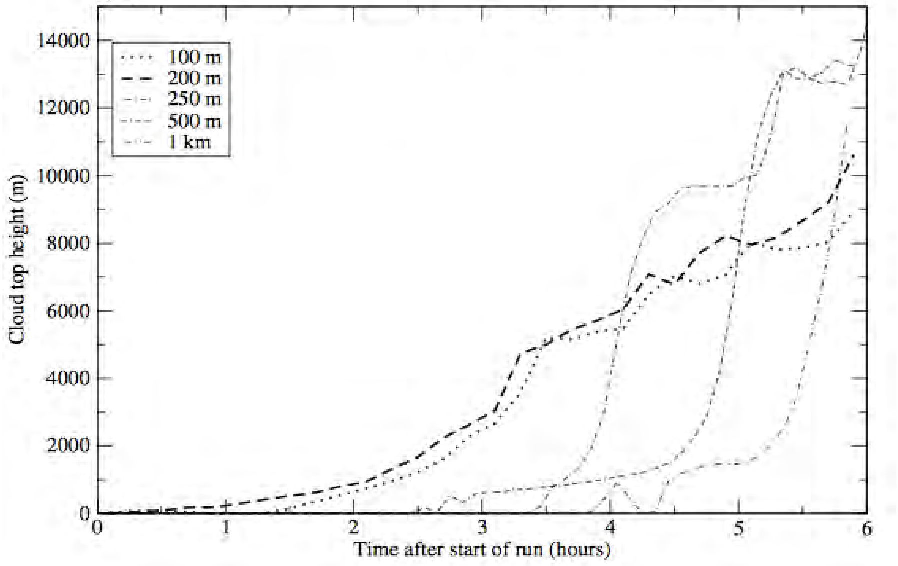
Scales of heterogeneity: Cloud←→turbulence at small scales

From Petch (2006, QJRMS)



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

Need ~100m resolution before start to get convergence
Turbulence and cloud closely linked



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

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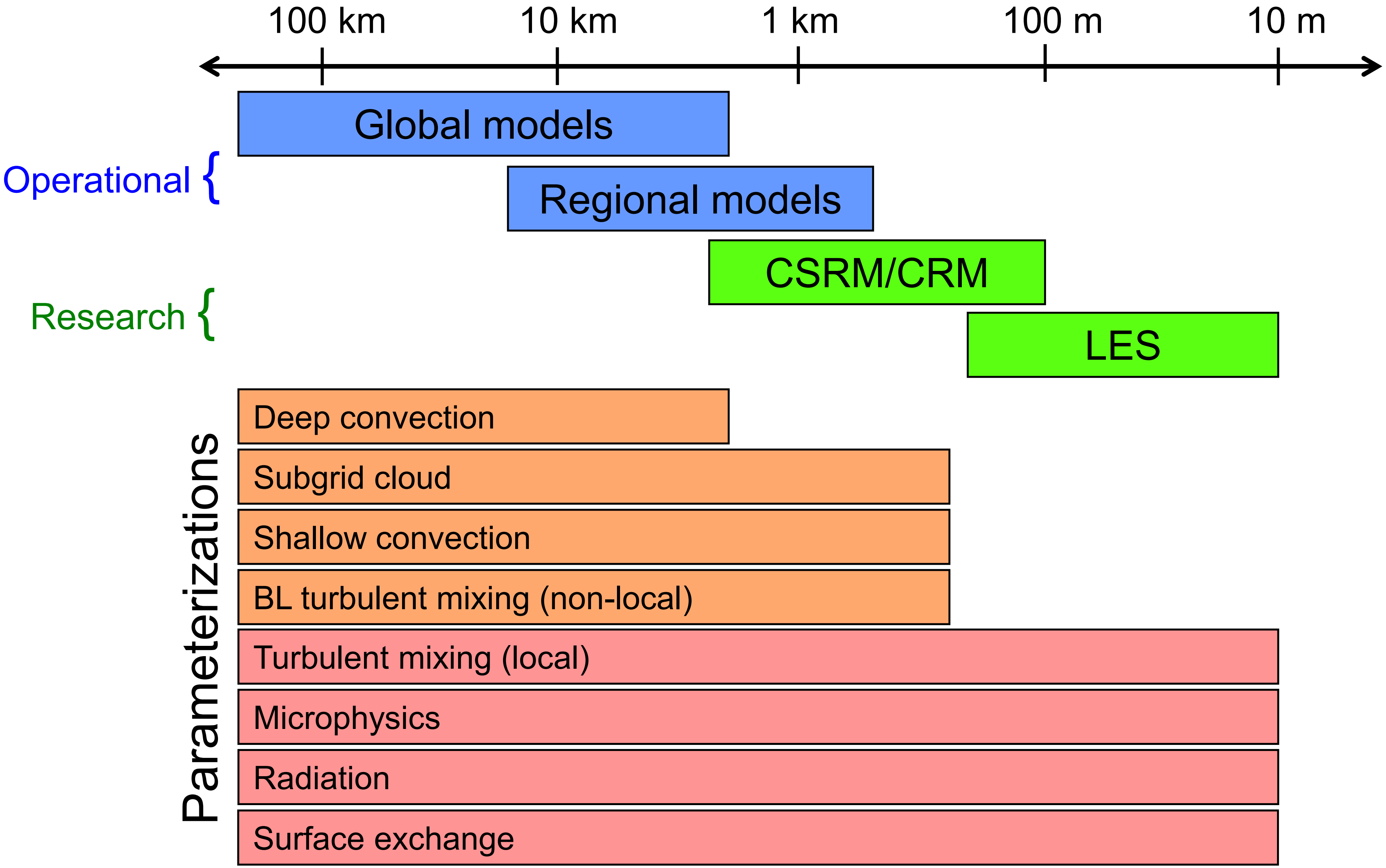
Scales of heterogeneity: Model parametrizations



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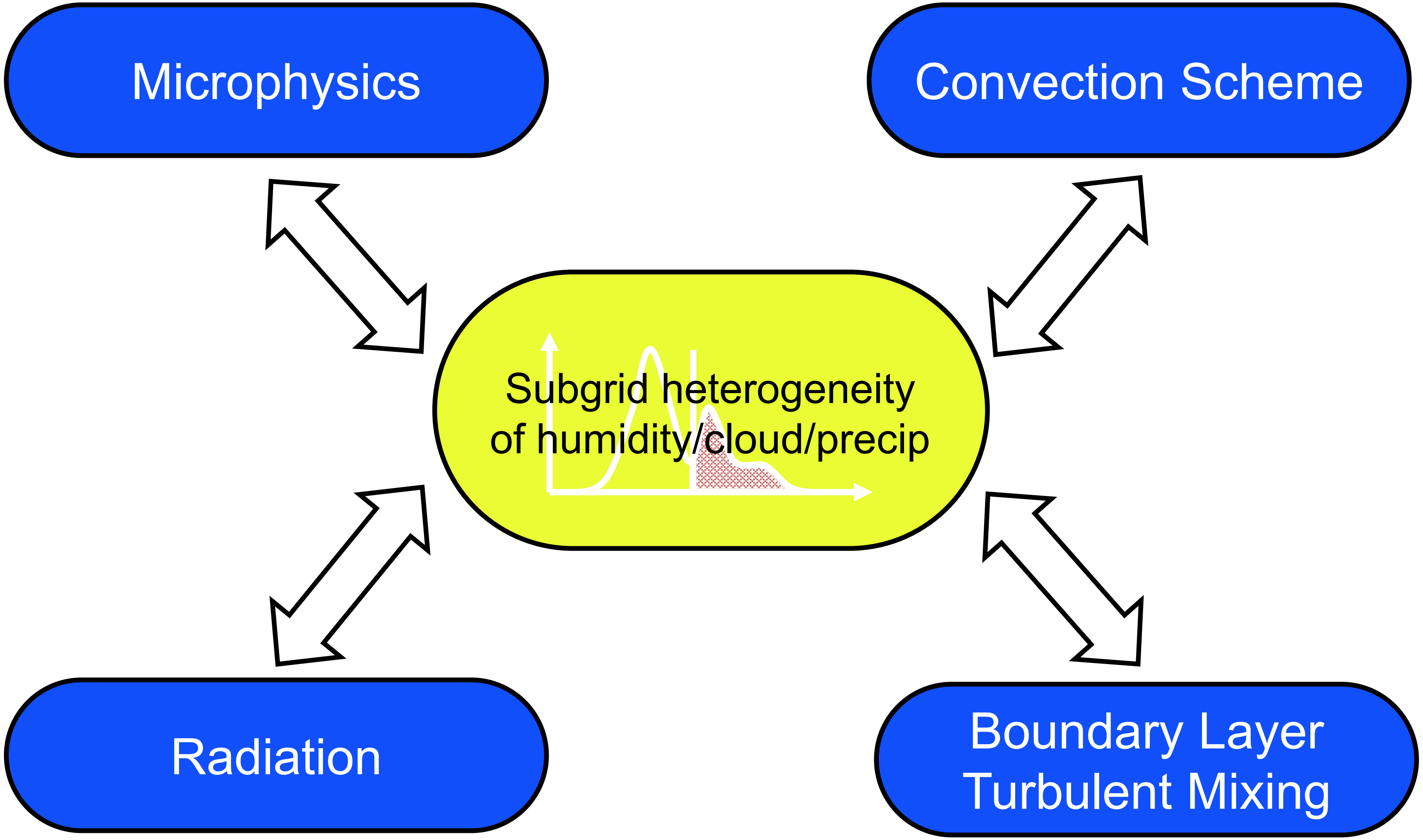
Scales of heterogeneity: Consistency across model parametrizations


Microphysics

Convection Scheme

Subgrid heterogeneity of humidity/cloud/precip

Radiation

Boundary Layer Turbulent Mixing

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Scales of heterogeneity: Summary

1. Humidity, cloud ←→ subgrid turbulence/convection
2. Important for radiation, precipitation, latent heating
3. Less important with increasing model resolution, but still relevant < 10km (regime dependent).
4. Stratiform cloud, convection, BL turbulence all part of the subgrid problem - towards a consistent representation across model parametrizations

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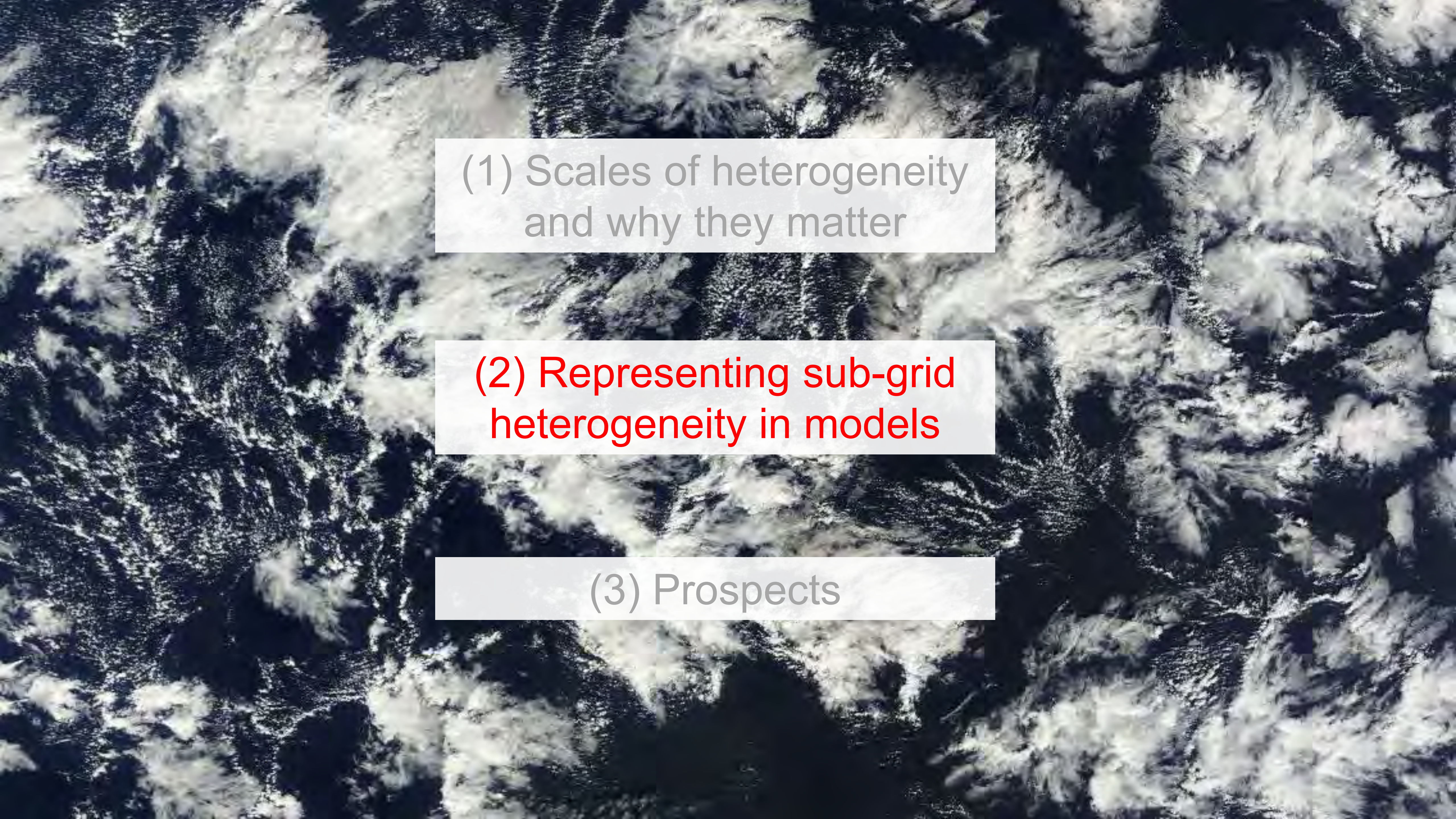
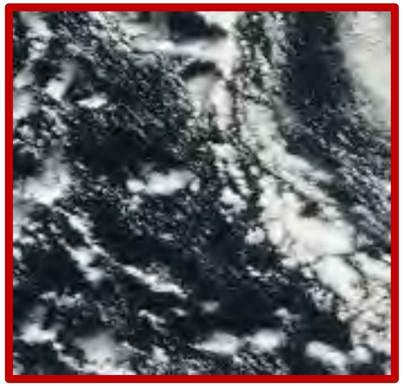


(1) Scales of heterogeneity and why they matter

(2) Representing sub-grid heterogeneity in models

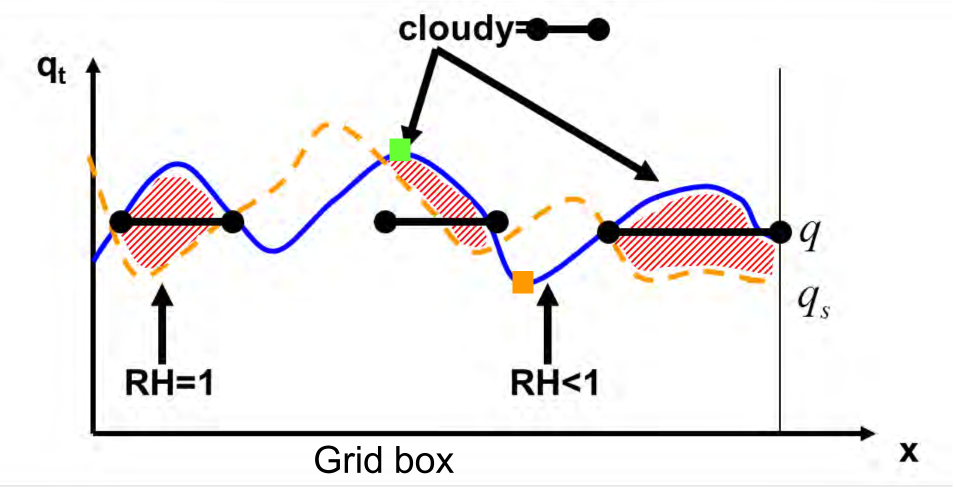
(3) Prospects

Representing sub-grid heterogeneity: PDF of total water



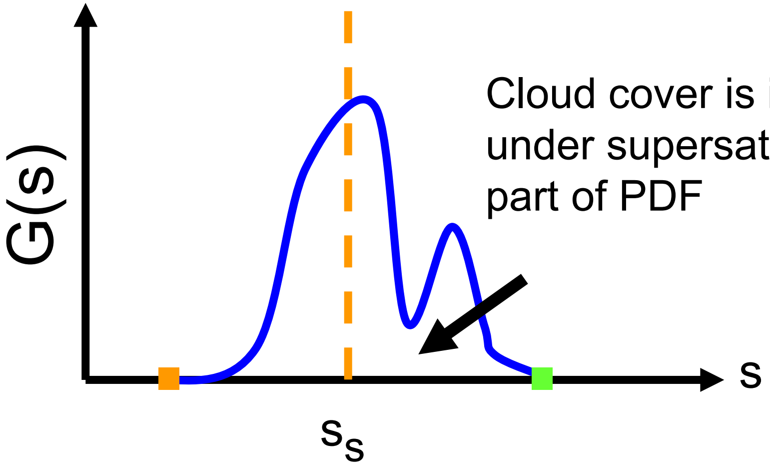
Statistical schemes explicitly specify the probability density function (PDF), *G*, for quantity, *s*, (or if assume T homogeneous, total water q_t) (Sommeria and Deardorff 1977; Mellor 1977)

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



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

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



Cloud cover is integral under supersaturated part of PDF

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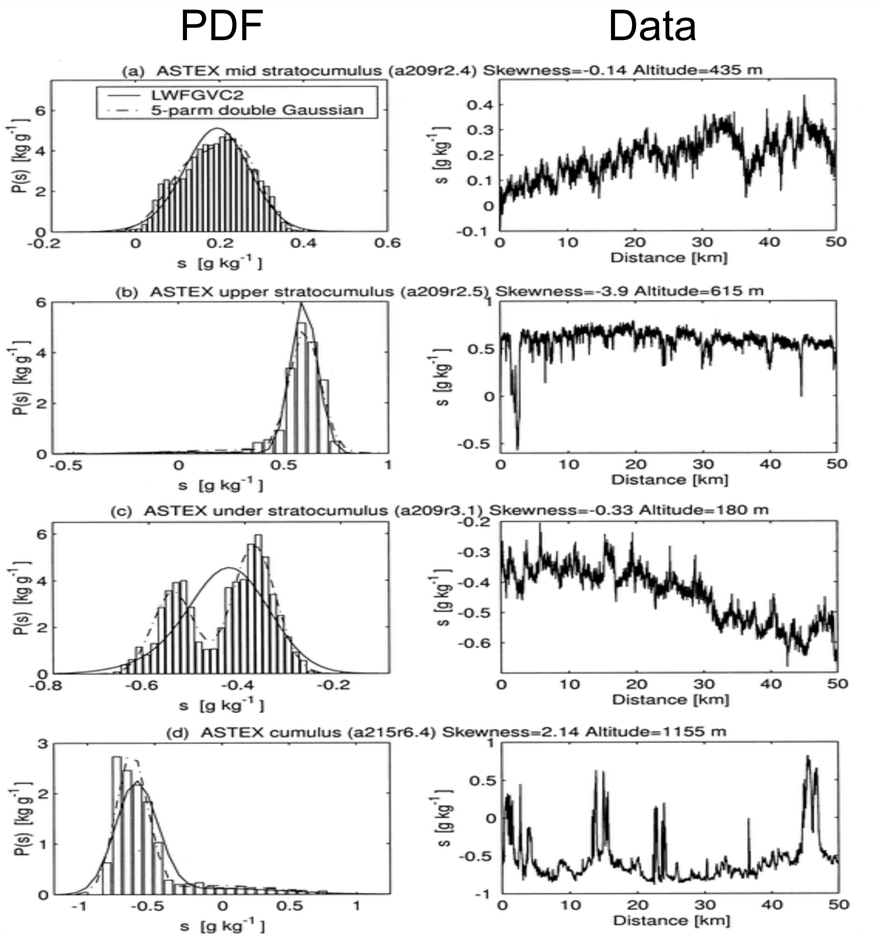
Representing sub-grid heterogeneity: Observed PDF of total water

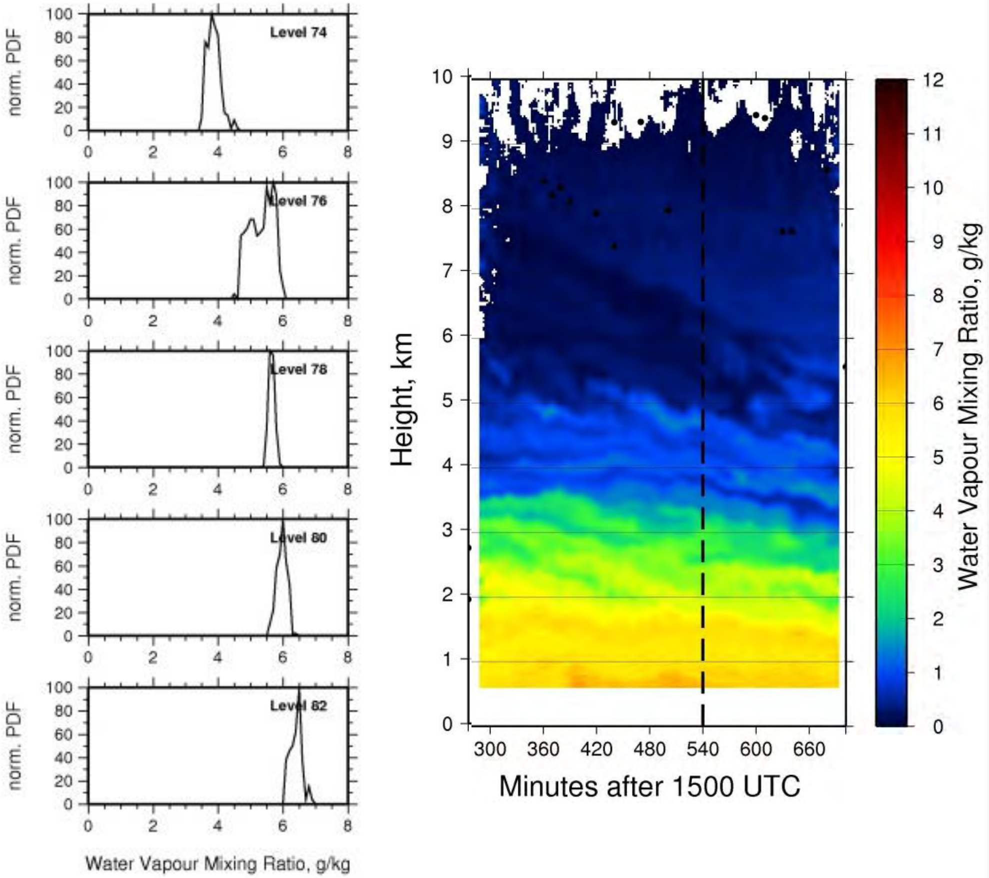
Observations from aircraft, tethered balloon, satellite, Raman lidar

…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)

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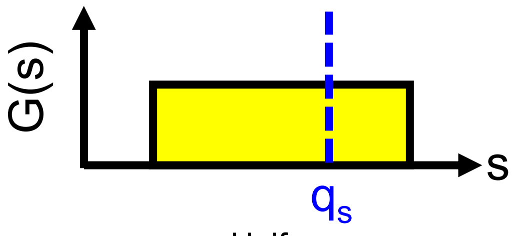
Representing sub-grid heterogeneity: Modelled PDF of total water

Represent with a functional form, specify the:

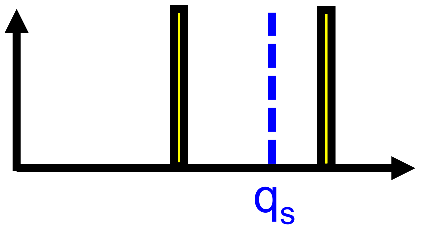
(1) PDF type (delta, continuous, unimodal, bimodal, symmetrical, bounded?)

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

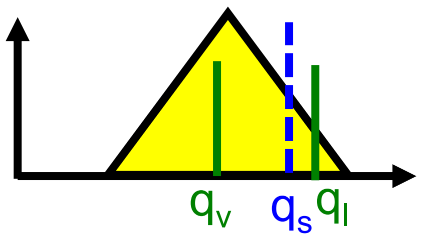
(3) Diagnostic or prognostic (how many degrees of freedom?)



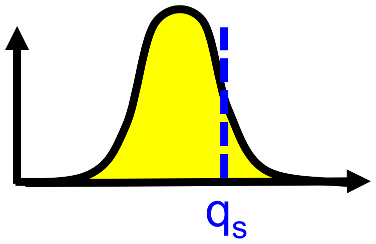
Uniform:
Sundquist (1978)
Letreut and Li (1991)



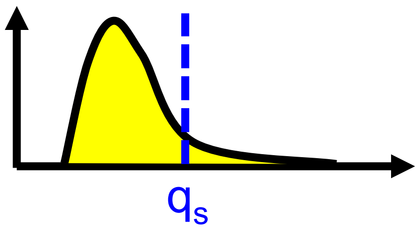
Double Delta Fn:
Randall et al. (1992)
Lappen and Randall (2001)



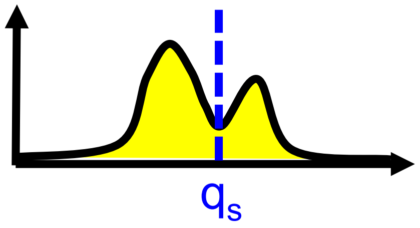
Triangular:
Smith (1990)



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)

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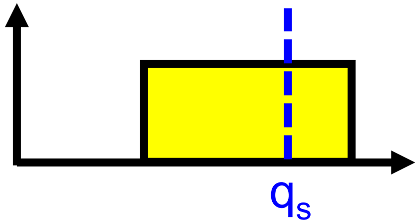
Representing sub-grid heterogeneity: Sundquist (1989) – form use in many GCMs

(1) Uniform

(2) Prognostic: Total water mean

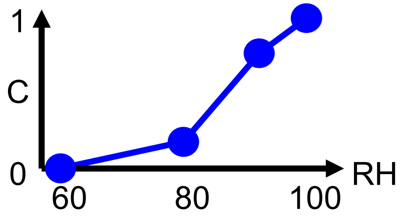
Diagnostic: Variance (width)

(3) 1 cloudy degree of freedom

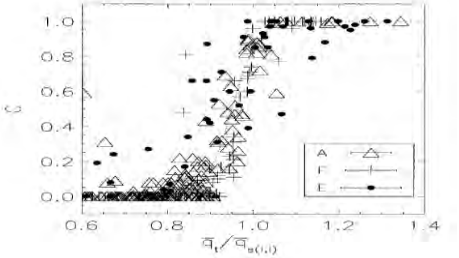


Advantages:

- First order approximation to obs
- Computationally inexpensive



Wood and Field (2000)



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)

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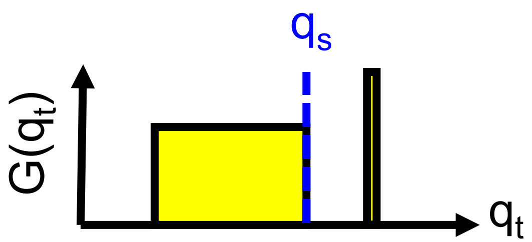
Representing sub-grid heterogeneity: Tiedtke (1993) – ECMWF IFS since 1995

(1) Uniform/delta function

(2) Humidity mean, condensate mean, cloud fraction

(3) 3 cloudy degrees of freedom



Advantages:

- Computationally inexpensive
- Sources and sinks for all processes
- Direct convective detrainment of condensate and cloud fraction important term
- Allows positive and negative skewness
- Number of tunable parameters
- Proven success in NWP

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

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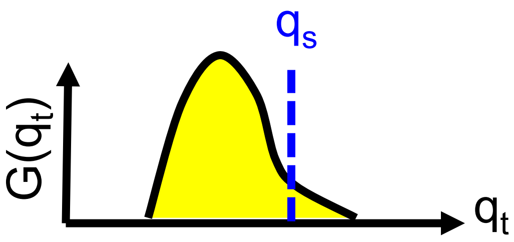
Representing sub-grid heterogeneity: Tompkins (2002) ECHAM

(1) Bounded Beta function with positive skewness

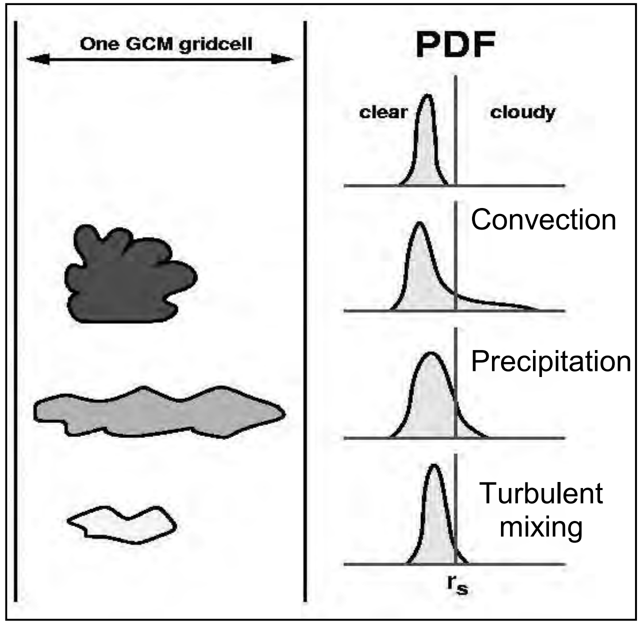
(2) Prognostic: Total water mean, condensate mean, upper bound

(3) ~3 degrees of freedom



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)

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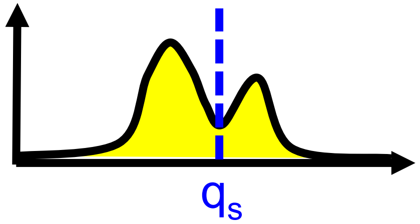
Representing sub-grid heterogeneity: Golaz et al (2002) – CLUBB

(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

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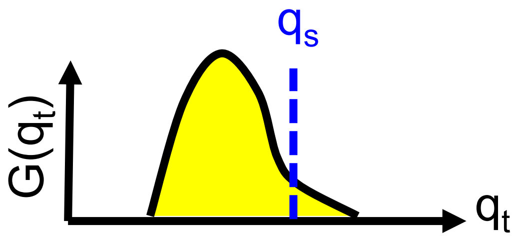
Representing sub-grid heterogeneity: Key characteristics for the PDF?



1. Condensation/evaporation – if $q_s(T)$ changes what is the change in cloud fraction & condensate?
2. Convection – increase of skewness (+ve, -ve)
3. Subgrid heterogeneity of condensate – for unbiased radiation, microphysics

- Ideally we would like to represent and predict the evolution of the whole PDF of total water (+ T,w,...)
- Achievable for warm-phase turbulent boundary layer? But elsewhere many difficulties and uncertainties in specifying sources and sinks (deep convection, ice phase, mixed phase)
- Given all the many uncertainties in NWP, is it good enough to assume a constant PDF just for the condensation and evaporation process, and then diagnose the heterogeneity of condensate and humidity?

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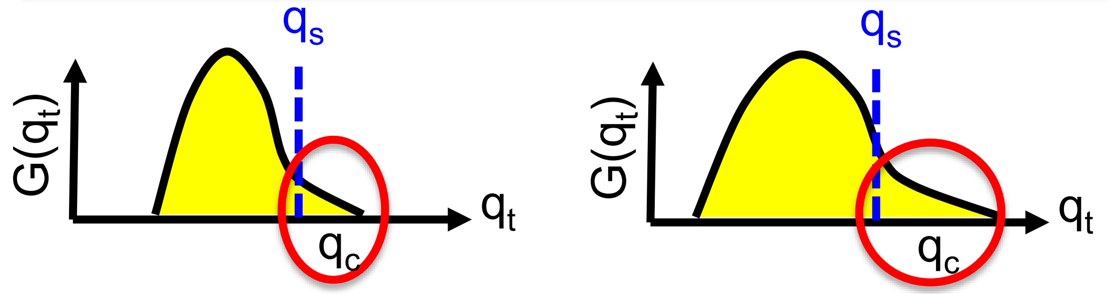
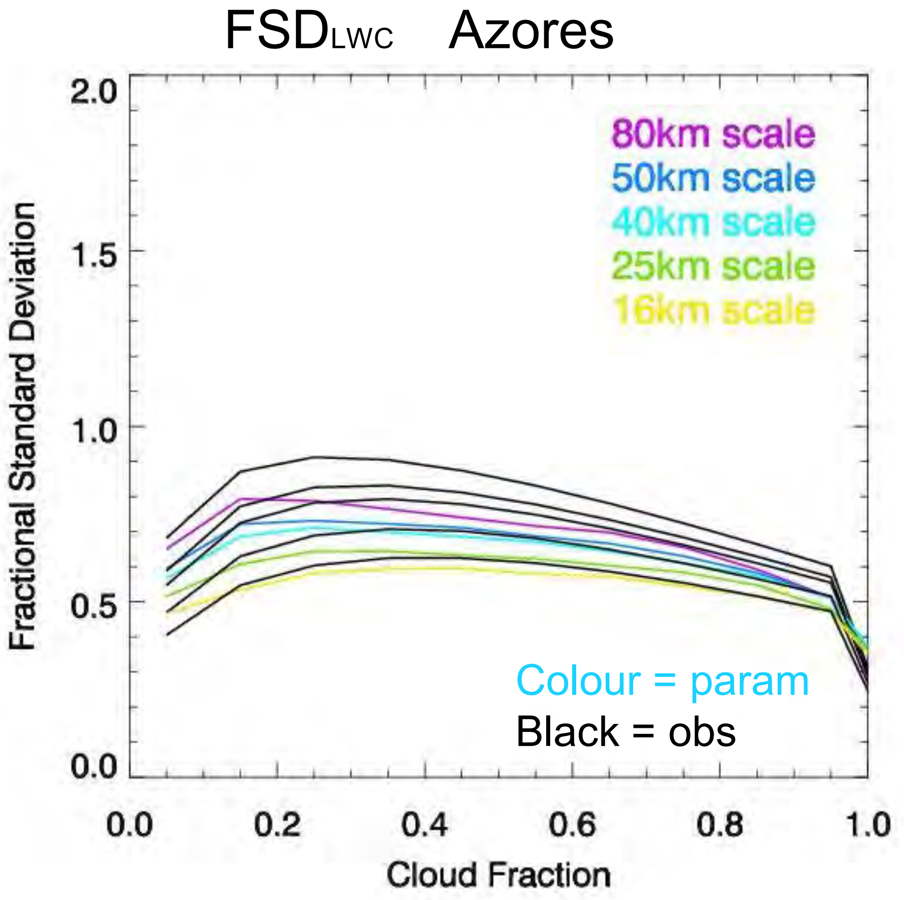
Representing sub-grid heterogeneity: Fractional standard deviation of condensate



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

FSD



Boutle et al. (2014)

Parameterize FSD as a function of cloud fraction and scale length and use with a PDF shape (log-normal)

$$FSD_l = \begin{cases} (0.45-0.25C)(xC)^{1/3}\left((0.06xC)^{1.5}+1\right)^{-0.17} & C<1 \\ 0.11(x)^{1/3}\left((0.06x)^{1.5}+1\right)^{-0.17} & C=1 \end{cases}$$

Captures the variation reasonably well at the mid-Atlantic Azores site

Use for radiation (McICA)
Use for microphysics

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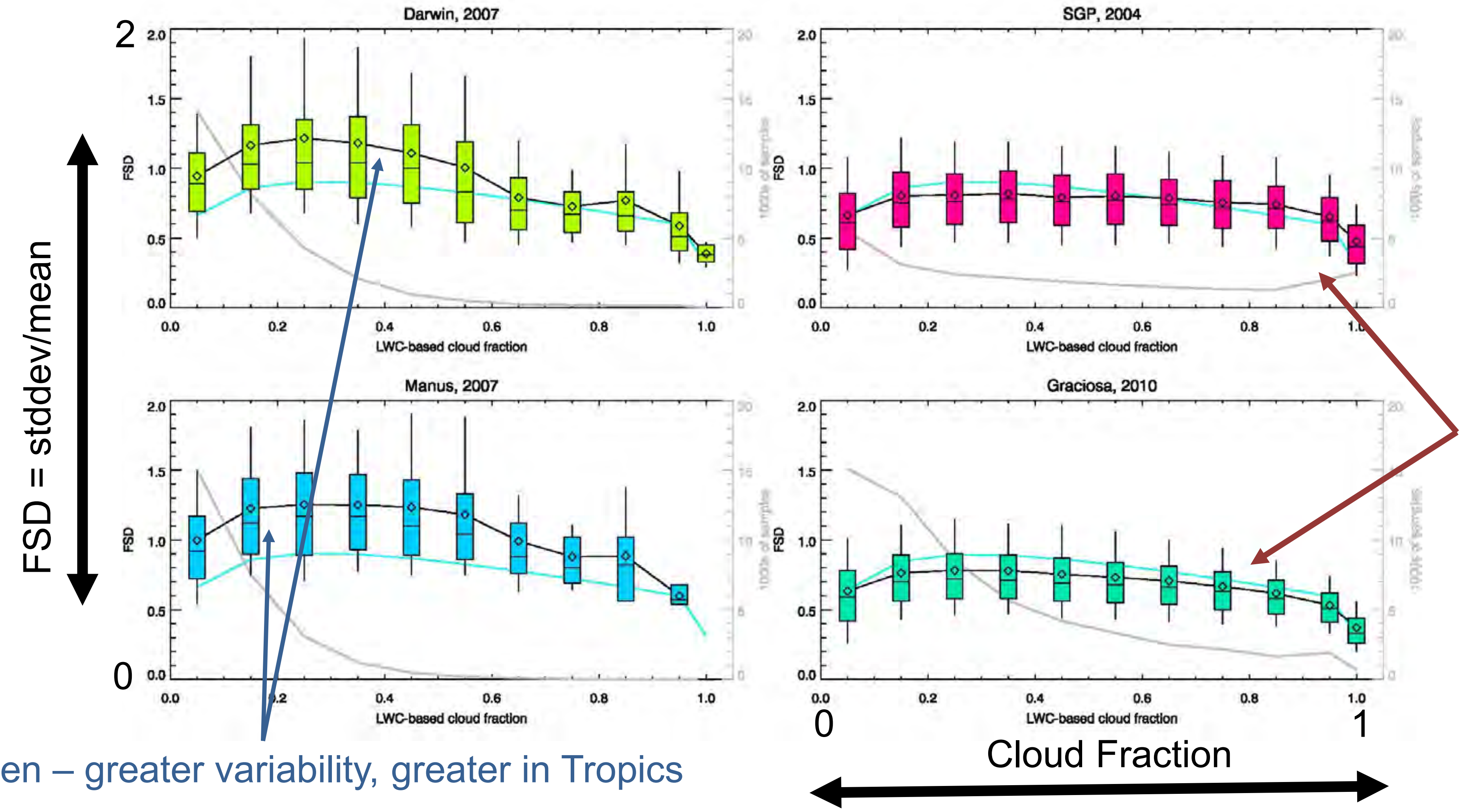
Representing sub-grid heterogeneity: How does observed FSD vary with regime?



Blue line is Boutle et al (2014) parametrization

Grey line is no. of obs

Black line, box and whiskers are observed

Overcast – more homogeneous, no cloud edges

Broken – greater variability, greater in Tropics

Function of cloud fraction only doesn't explain all the global spatial and temporal variability

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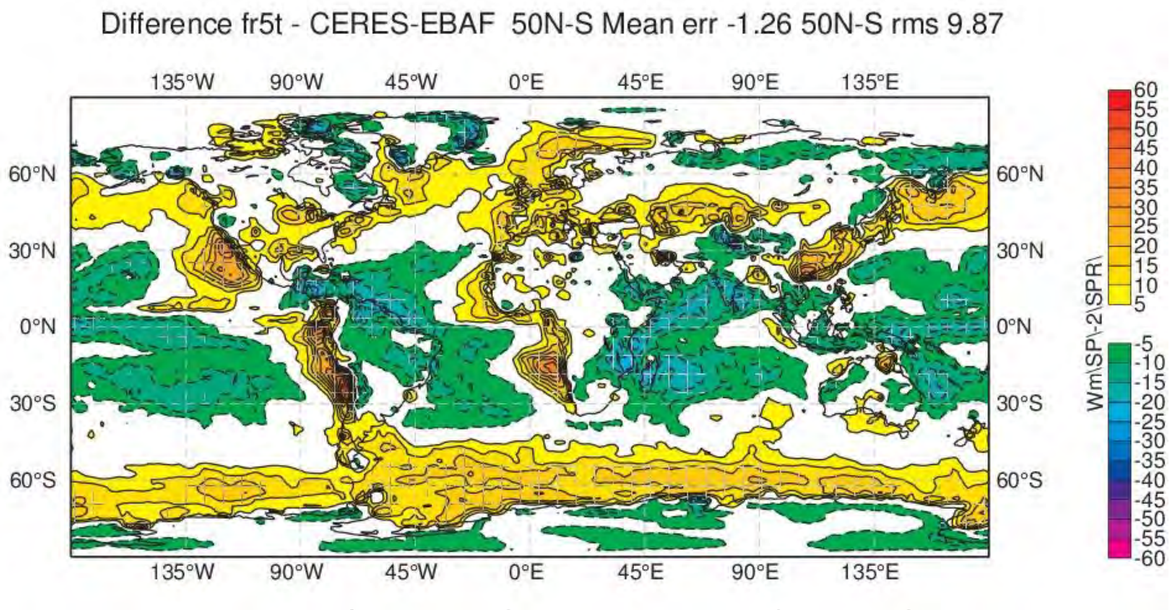
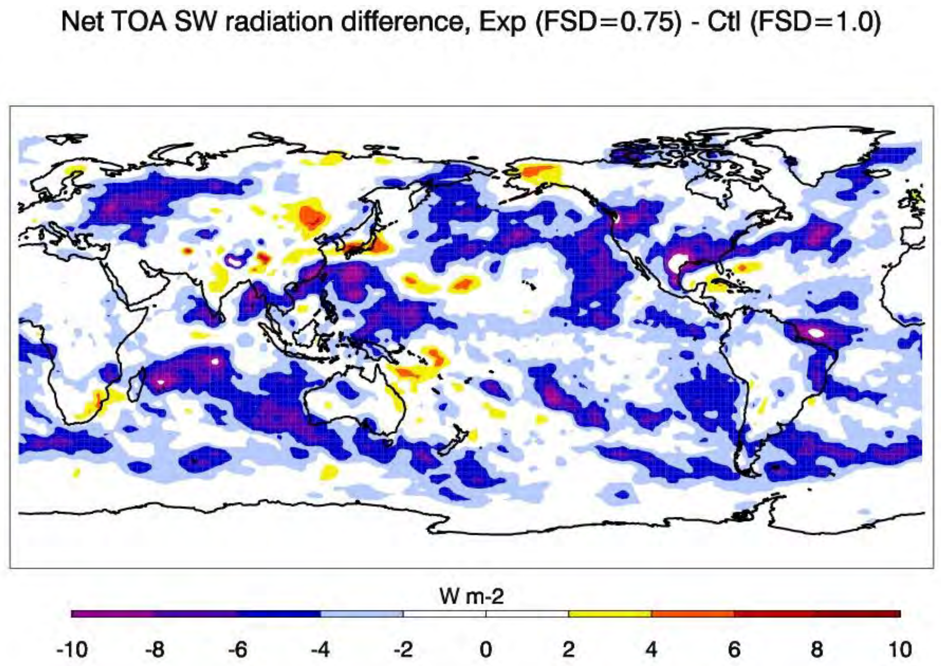
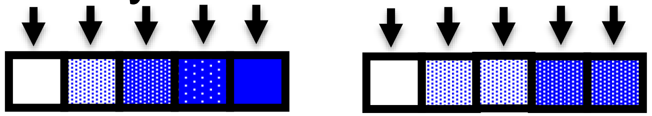
Representing sub-grid heterogeneity: Do FSD variations matter - radiation?


Difference fr5t - CERES-EBAF 50N-S Mean err -1.26 50N-S rms 9.87

Annual mean TOA net SW bias vs. CERES EBAF


Net TOA SW radiation difference, Exp (FSD=0.75) - Ctl (FSD=1.0)

- The impact on TOA SW radiation of changing FSD from 1 to 0.75 globally in the radiation scheme for liquid clouds is on the order of 5-10W/m^2.



- Generally more reflective - helpful in some places, but not in others.
- Potential to address regional biases!

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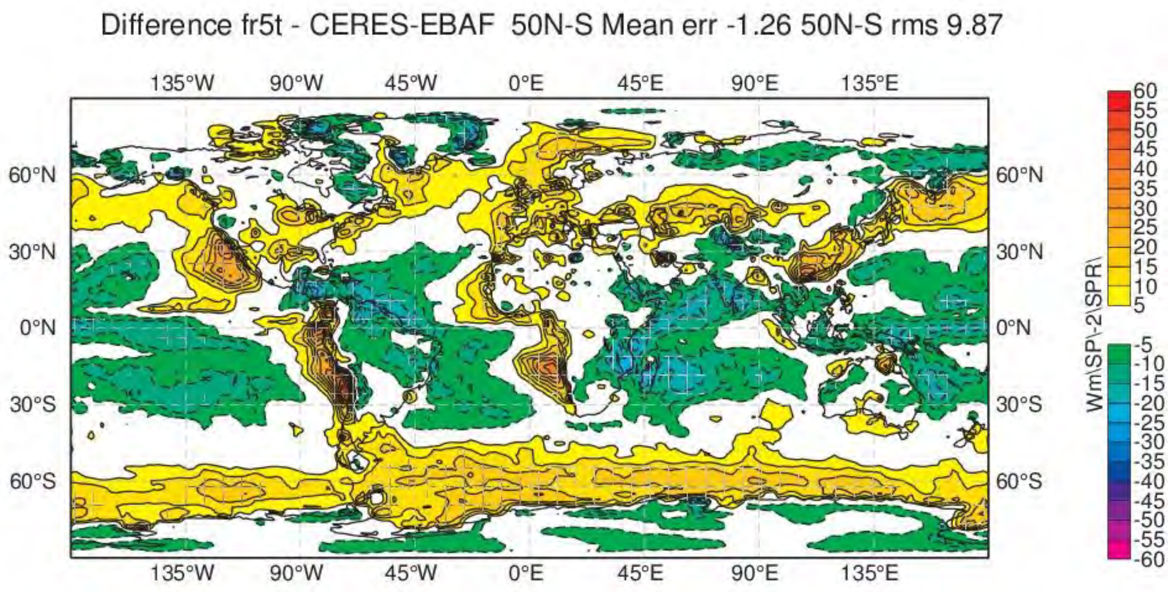
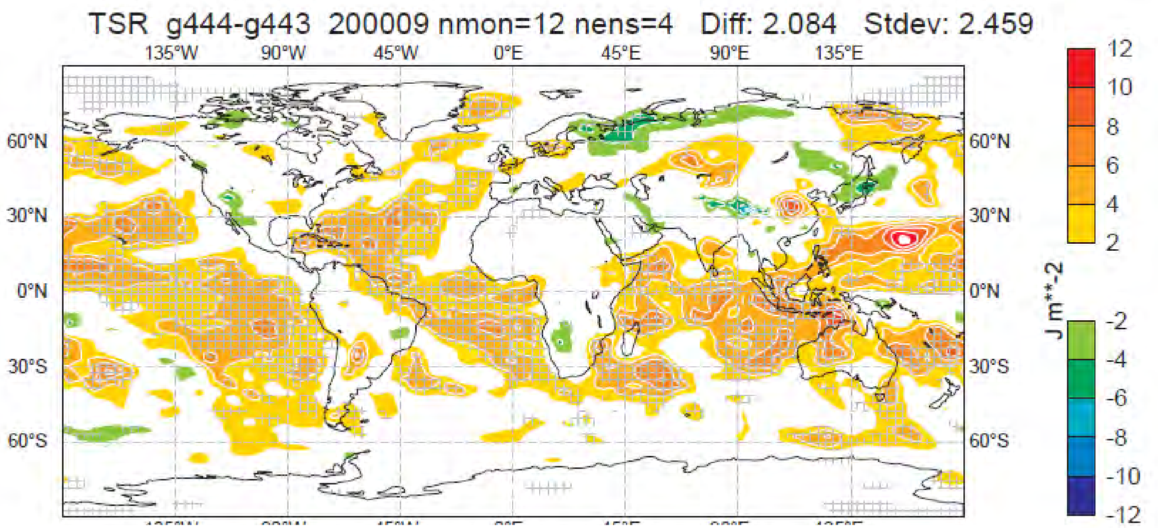
Representing sub-grid heterogeneity: Do FSD variations matter - microphysics?

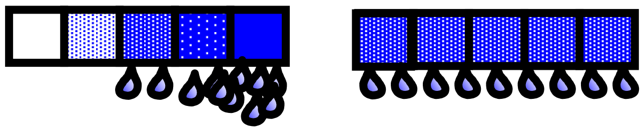


Annual mean TOA net SW bias vs. CERES EBAF



Difference (autoconv heterogeneity) – (control)

- The impact of including heterogeneity (Boutle et al 2014 parametrization) in the IFS warm-rain autoconversion/ accretion on TOA SW radiation is on the order of 5 Wm^{-2}.
- Increases autoconversion, reduced LWC, less reflective.
- Again, potential to address regional biases.



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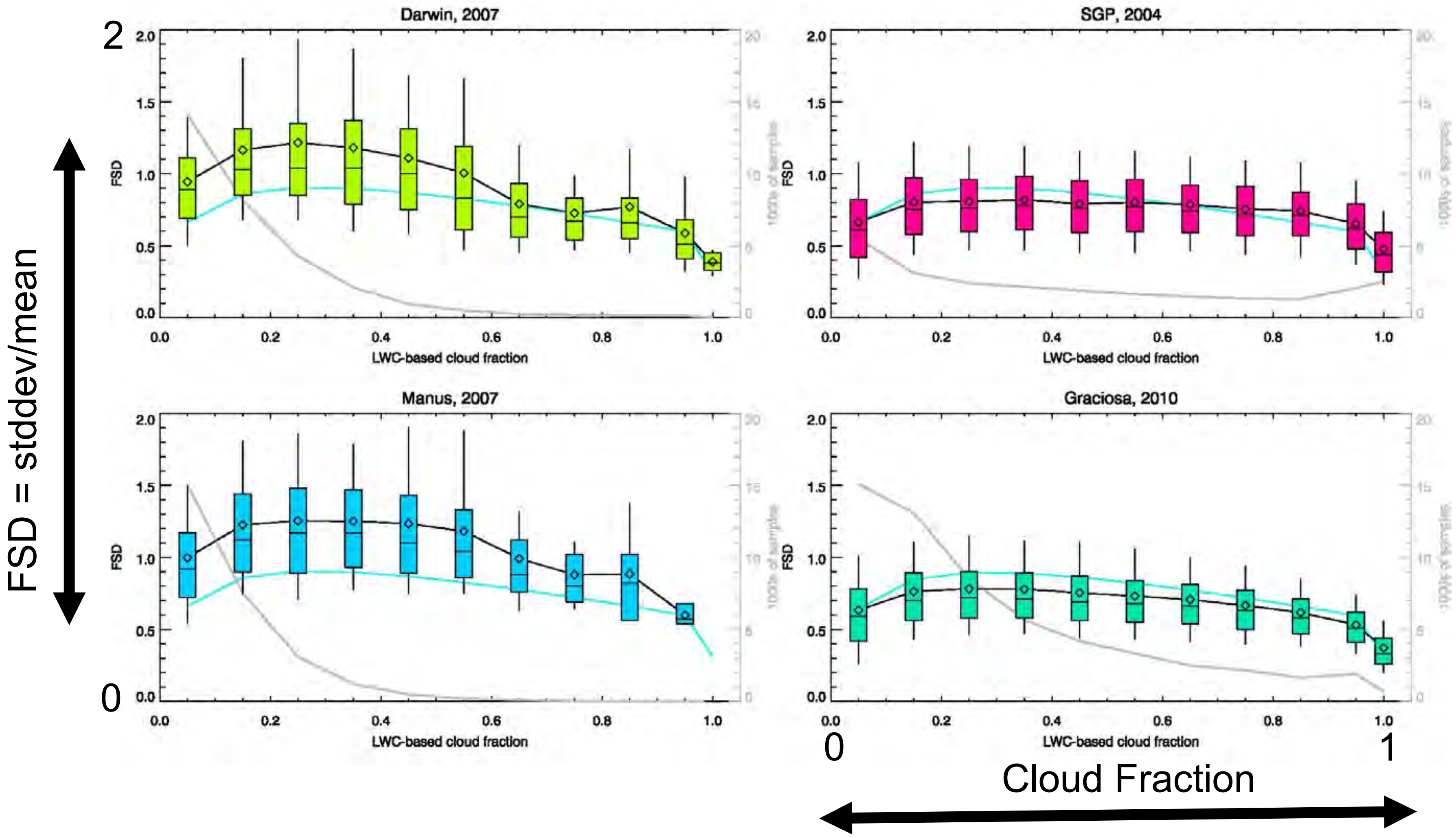
Representing sub-grid heterogeneity: How does observed FSD vary with regime?



Blue line is Boutle et al (2014) parametrization

Grey line is no. of obs

Black line, box and whiskers are observed

Function of cloud fraction only doesn’t explain all the global spatial and temporal variability

What else controls the heterogeneity – convective updraught strength, cloud size, cloud depth…?

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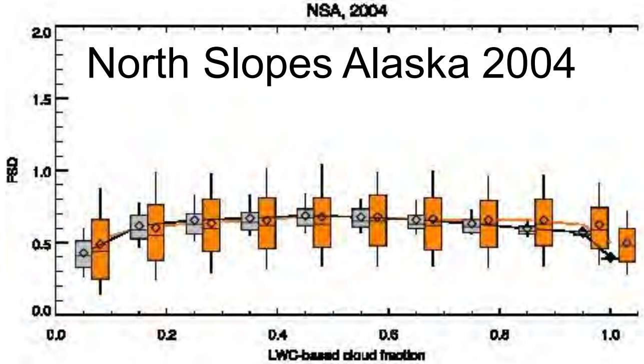
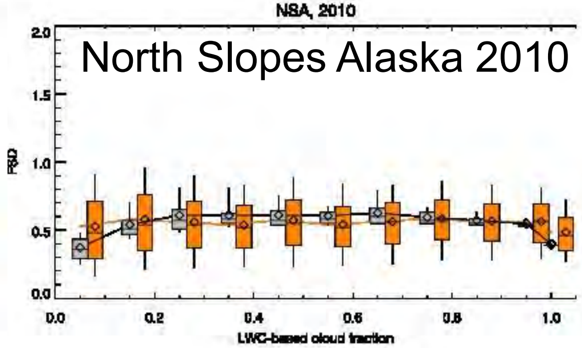
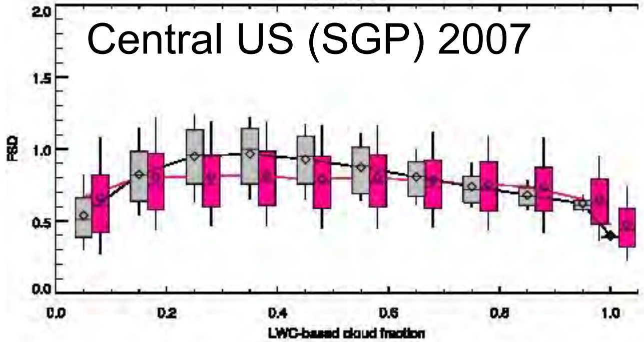
Representing sub-grid heterogeneity: If FSD also a function of q_t mean…

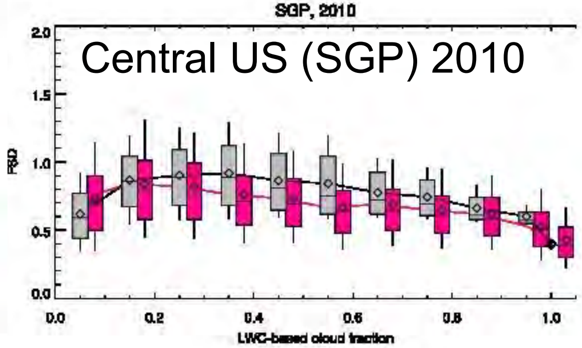
Captures the range of FSD values between sites and years

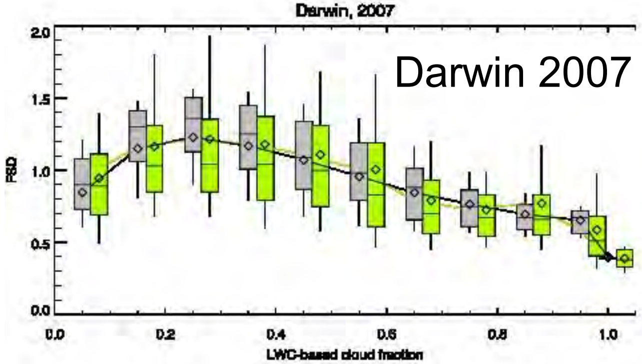
Ahlgrimm and Forbes (2016)

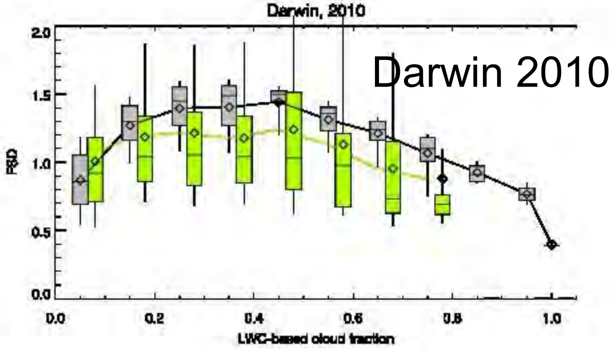

North Slopes Alaska 2004

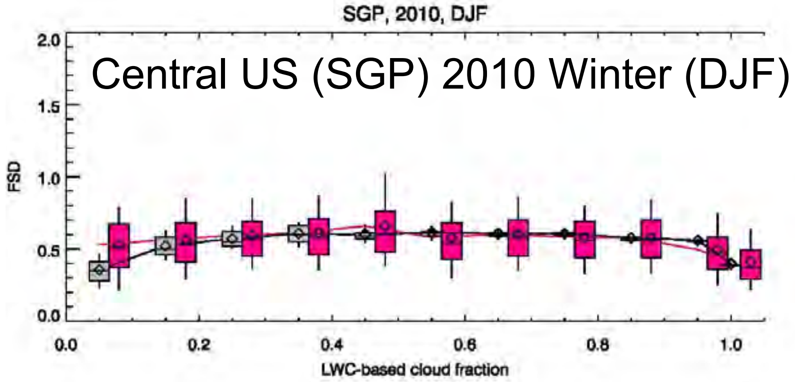

North Slopes Alaska 2010

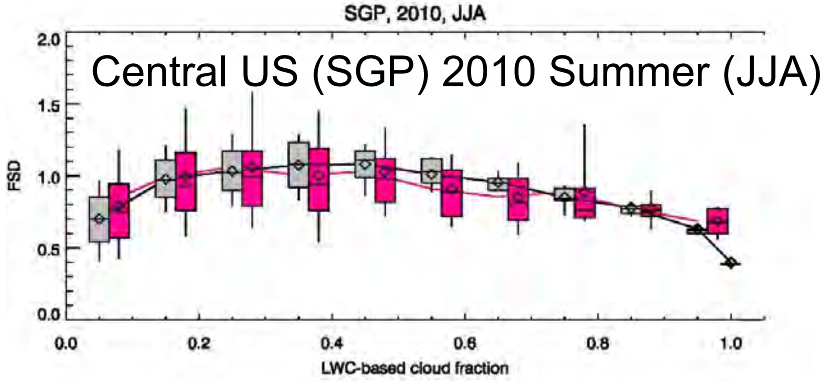

Central US (SGP) 2007


Central US (SGP) 2010


Darwin 2007


Darwin 2010


Central US (SGP) 2010 Winter (DJF)


Central US (SGP) 2010 Summer (JJA)

Good interseasonal variation

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Representing subgrid heterogeneity: Summary

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, at least in part, 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. Prognostic cloud fraction schemes successful (e.g IFS, Met Office PC2). Full PDF not always assumed for every process but key components represented (cond/evap, skewness).
5. Cloud condensate (liquid, ice) heterogeneity for radiation and microphysics can be represented with fractional standard deviation concept – well described by function of cloud fraction, mean total water mean and grid box size.

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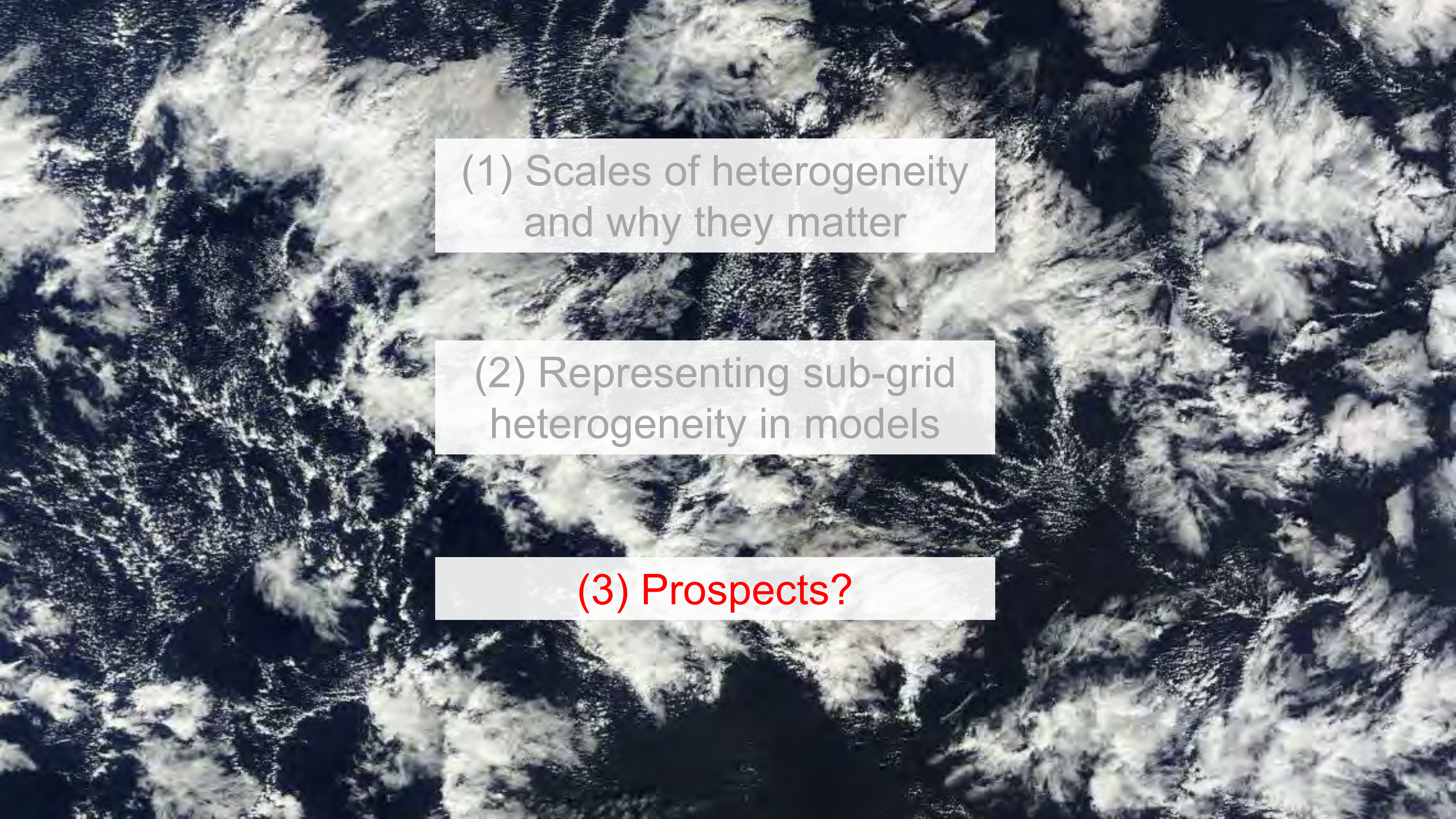


(1) Scales of heterogeneity and why they matter

(2) Representing sub-grid heterogeneity in models

(3) Prospects?

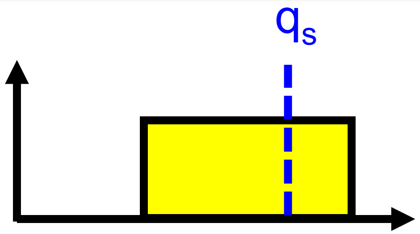
Prospects?

Diagnostic statistical (RH) schemes

(Sundquist 1989; Smith 1990, Xu and Randall 1996)

C = fn(RH,…)

X



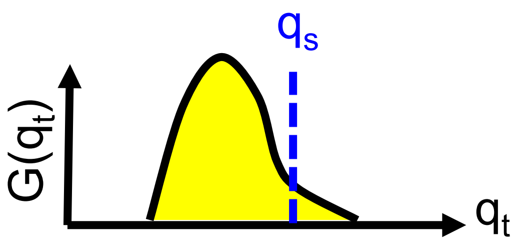
$$C = 1 - \sqrt{\frac{1-RH}{1-RH_{crit}}}$$

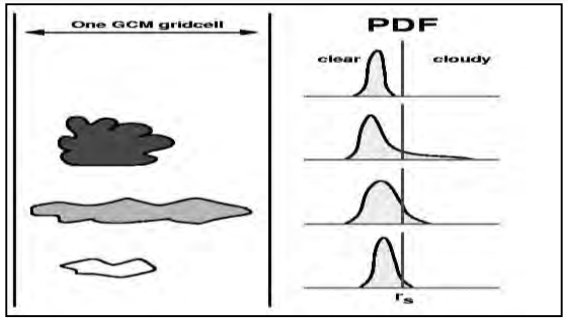
Prognostic q_t PDF schemes

(Tompkins et al. 2002; Weber et al. 2011)

q_t mean, variance, skewness

?



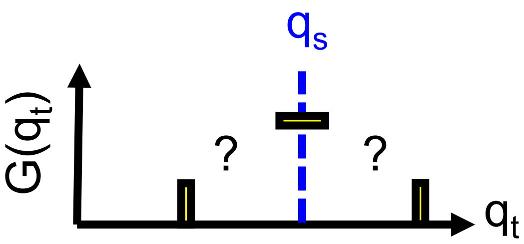


Prognostic cloud fraction schemes

(Tietdke 1993; PC2 Wilson et al. 2008)

Humidity, condensate, cloud fraction

?



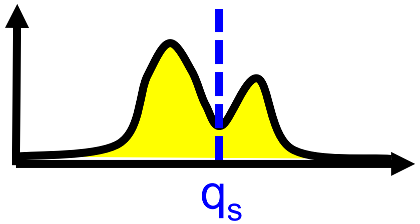
+ assumed PDF of condensate/precip

Prognostic high-order closure schemes

(Golaz et al. 2002; 2007; Larson et al. 2012)

$w, \theta_l, q_t, w'^2, \theta_l'^2, q_t'^2, w'\theta_l', w'q_t', \theta_l'q_t', w'^3$

?



Unified turbulence and cloud

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Prospects? 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

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Prospects? Some summary comments

- Representing sub-grid cloud gets less important as models go to higher resolution, but still required sub-10km.

- BL turbulence, shallow convection, deep convection, cloud scheme are all part of the sub-grid problem. Towards unification in the future? – different approaches…

- High order closure turbulence schemes unifying BL/Cu processes with assumed PDF seem to work well for liquid-phase turbulent boundary layers, but complexity(?), computational cost(?), only part of the solution (what about deep convection, outside BL?). Can mass flux convection, BL turbulence, cloud parametrization be simpler, more efficient and give as good results?

- For all schemes, still difficulties including subgrid ice phase, mixed-phase, precipitation, vertical overlap.

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

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Questions?