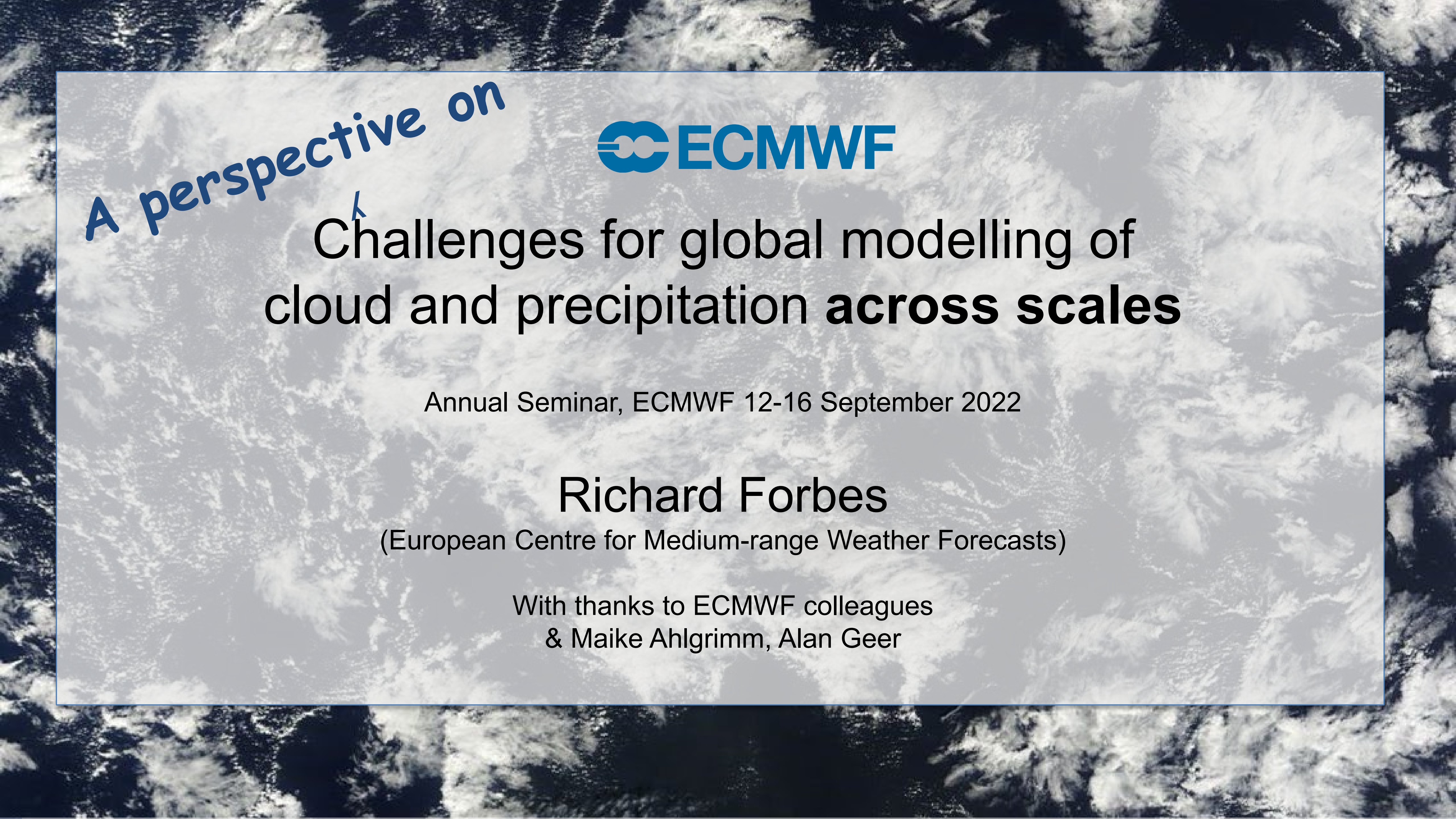


A perspective on

Challenges for global modelling of cloud and precipitation **across scales**

Annual Seminar, ECMWF 12-16 September 2022

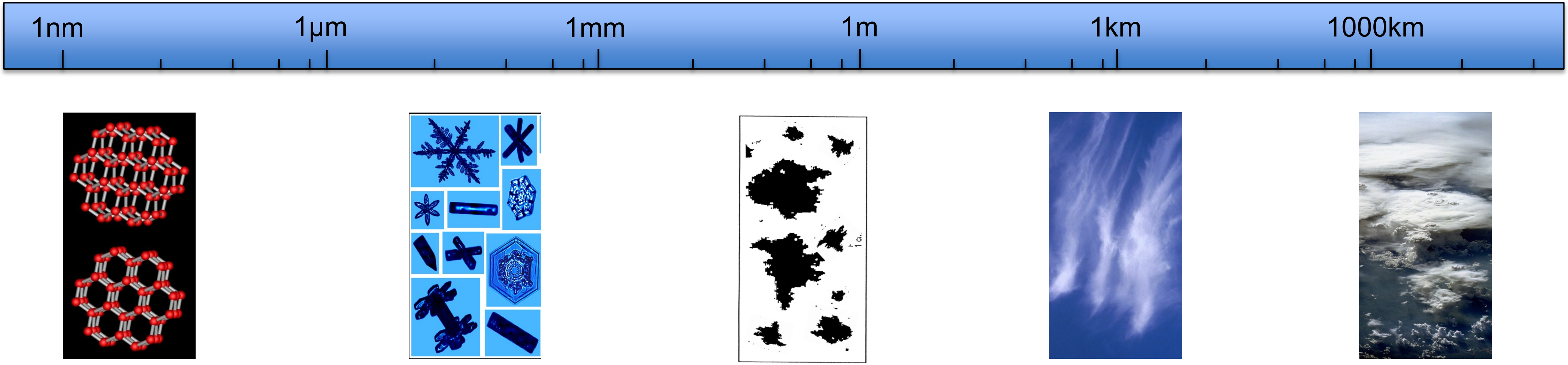
Richard Forbes
(European Centre for Medium-range Weather Forecasts)

With thanks to ECMWF colleagues
& Maike Ahlgrimm, Alan Geer

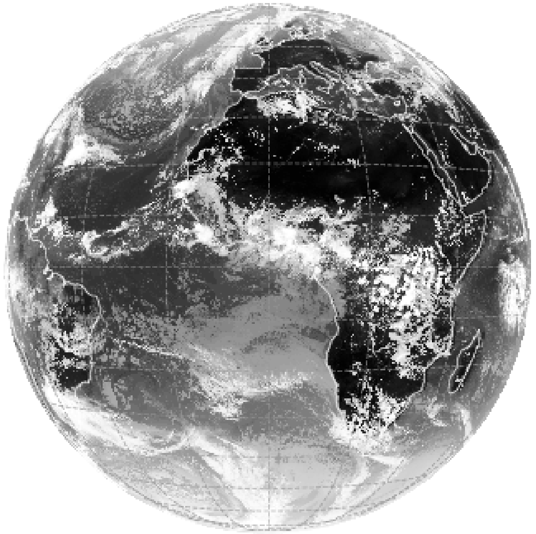
Challenges for global modelling across scales at ECMWF

1. Improving the **skill and realism** of global NWP **across timescales**
2. Increasing global model resolution **towards the km-scale**
3. Representing **model uncertainty** for ensemble prediction
4. Constraining models with **observations** globally

Cloud and precipitation: From the micro-scale to the global-scale



Uncertainties in representing processes across all scales can have global impacts



“Uncertainties in representing processes across all scales can have global impacts”

1. Useful to understand how our models represent cloud and precipitation processes across scales (it’s not always as clear cut as you might expect!)

2. How are we improving this representation across scales and why is it important?

3. We are developing our models from low resolution to high resolution. Would they look very different if we were going the other way round?

$$R' = a\bar{L}^{b}$$

Parametrization of precipitation formation

Rate of rain generation

Gridbox mean liquid water

$$R' = a\bar{L}^{b}$$

Parameters

- An autoconversion(+accretion) equation describing the process of rain drop formation from cloud droplet collision-coalescence

- The most important equation in the cloud microphysics schemes for NWP/climate modelling

- This is the simplest form (Kessler-type scheme). Other forms include dependence on droplet number, size, relative dispersion…. (e.g. Liu and Daum 2004, Liu et al. 2006 for an overview)

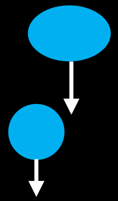
Parametrization of precipitation formation

1. What is this equation representing in a global model?

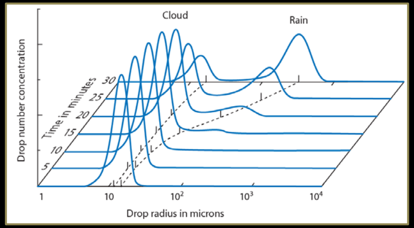
2. How do we define the uncertainties? Through a and b? Or processes that affect a and b at each scale? Or just discover a and b through machine learning?

$$R' = a\bar{L}^{b}$$

1. The microphysics of the sedimentation and collision-coalescence of water particles

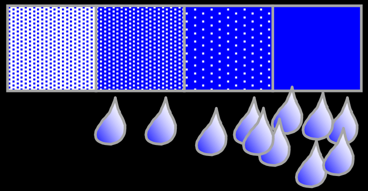


2. The combined effect of collision-coalesecence integrated across the size distributions of cloud and rain drops

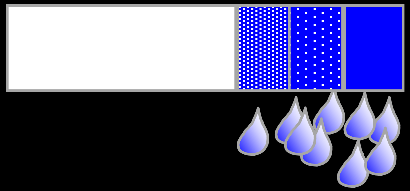


(After Berry and Reinhardt 1974)

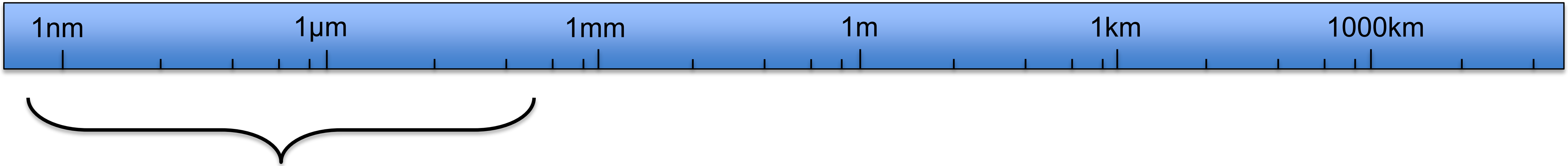
3. The effect of the variability of cloud and rain drop distributions within the cloud



4. The fractional part of the grid box that is covered by the cloud (some models use in-cloud L)



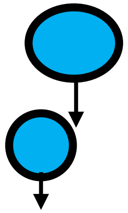
Examples of cloud and precipitation parametrization at different scales:

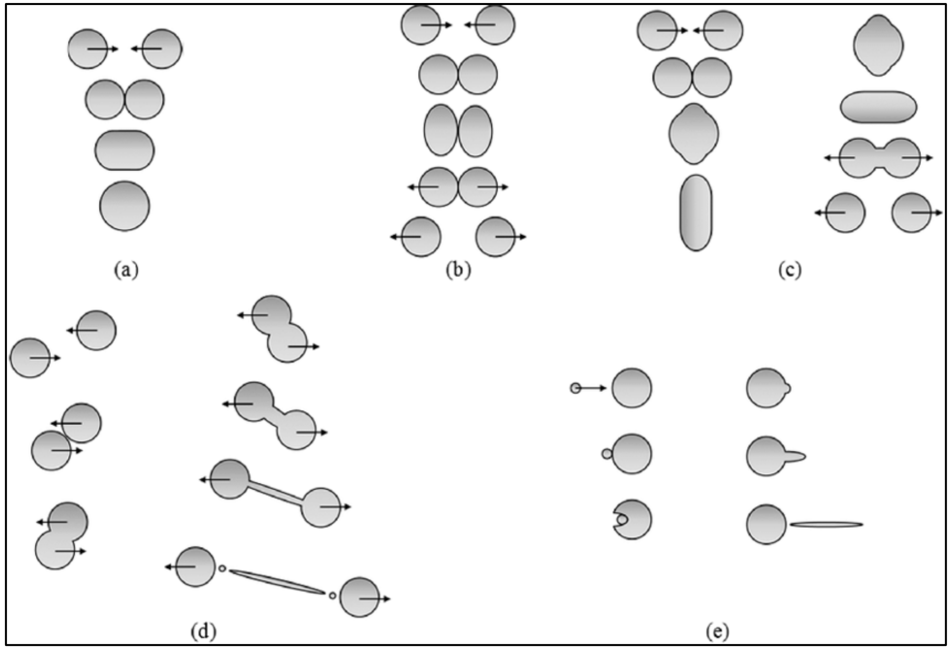


(1) Microphysics at the particle scale

Collision-coalescence of two water particles

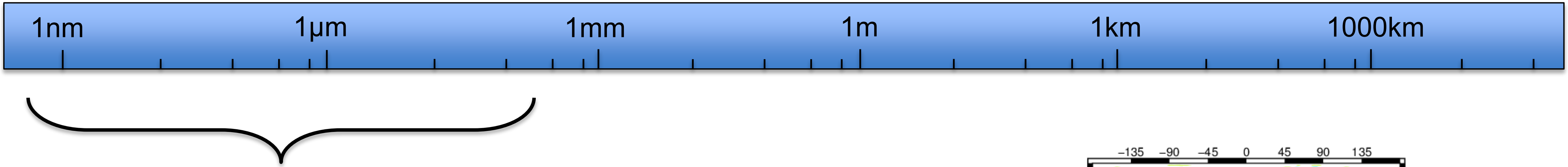
- Uncertainties in coalescence efficiency due to bouncing, disruption (e.g. Pruppacher and Klett 1997, Ch14)
- A systematic error in coalescence efficiency would have a systematic impact on the autoconversion rate





Regimes of droplet-droplet collisions (in the lab)
(From Charalampous et al. 2017)

Examples of cloud and precipitation parametrization at different scales:



(1) Microphysics at the particle scale

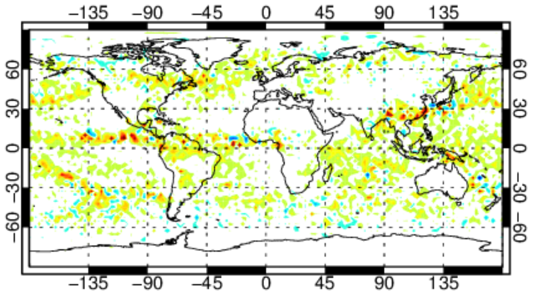
Collision-coalescence of water particles

Don't know the uncertainties

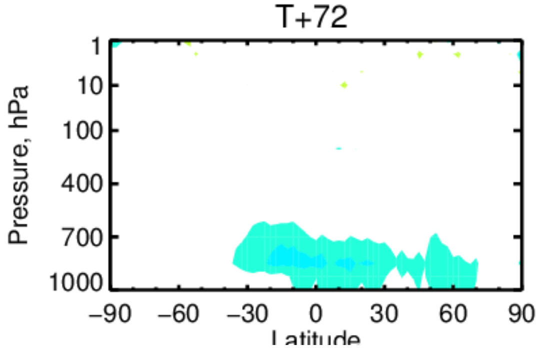
But a sensitivity experiment, e.g. reducing autoconversion/accretion by 30%

- Increases liquid water path, more SW reflection
- Cools lower troposphere and higher RH
- Significant enough to see improvement/degradation in NWP

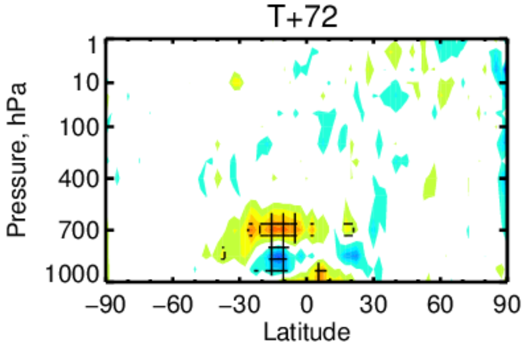
Increase in LWP (10-20 gm^{-3})



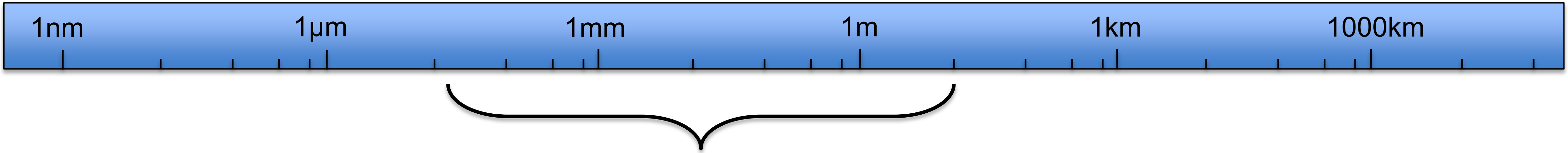
Cooling of lower troposphere (0.1K)



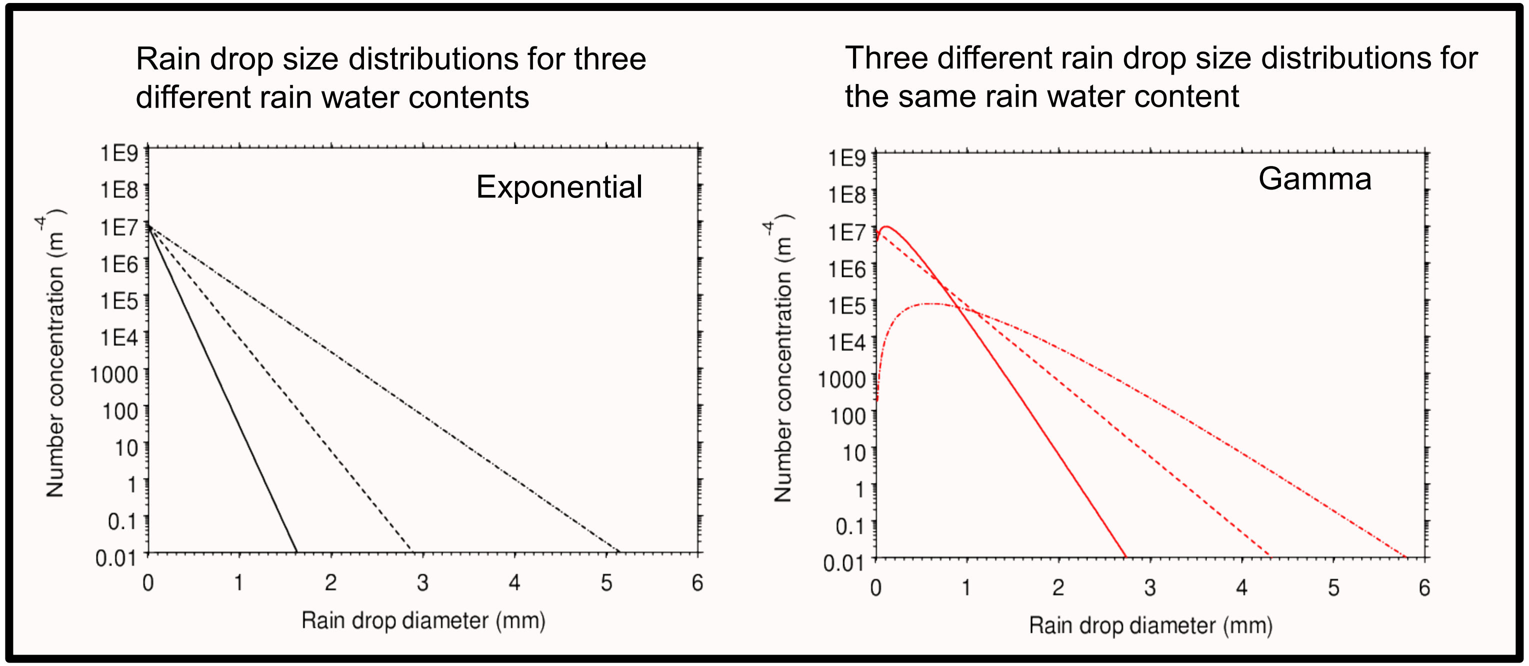
Change in temperature RMSE (few %) (blue improved, red degraded)



Examples of cloud and precipitation parametrization at different scales:



(2) Particle Size Distributions


Rain drop size distributions for three different rain water contents

Three different rain drop size distributions for the same rain water content

- Single- (mass) or double- (number) moment representations to define the PSDs are common
- For rain, can affect fall speed, accretion, evaporation…

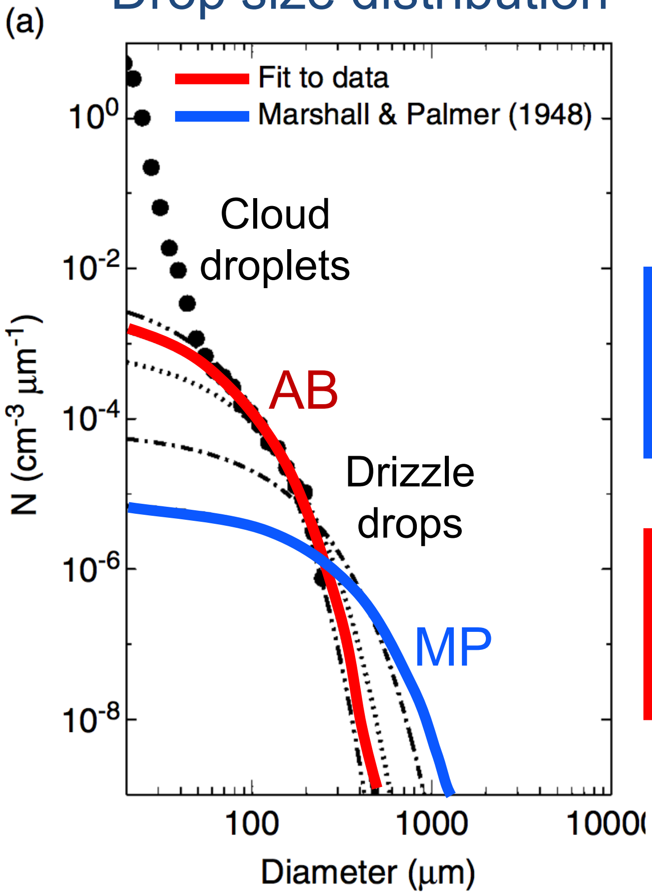
Rain drop size distribution matters for evaporation

Observations show there are **many more small droplets in drizzle that evaporate faster** (compared to heavier rain which generally follows a Marshall-Palmer DSD)

Drop size distribution

$$N(D) = N_0 D^{\mu} \exp(-\lambda D),$$

D = drop diameter
λ = slope of the DSD
μ = shape parameter



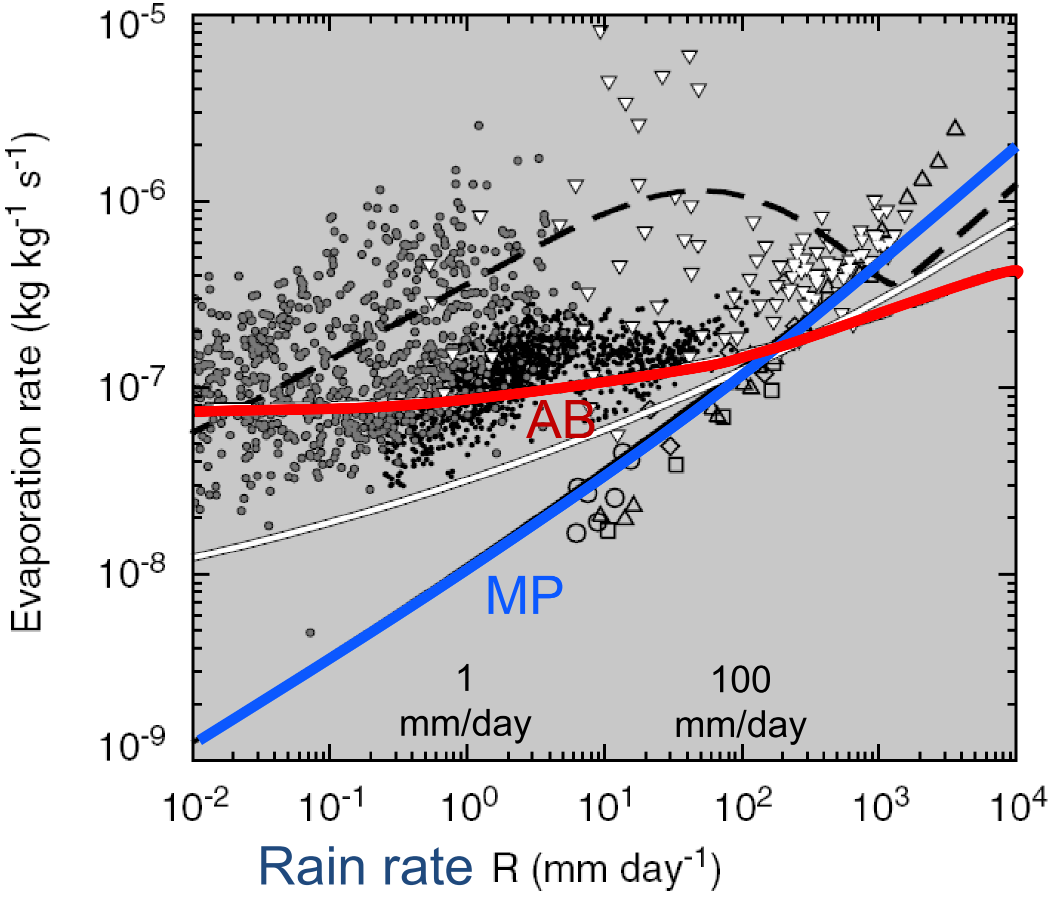
Marshall-Palmer (1948)

N_0 = 8x10^6 (μ=0)

Abel and Boutle (2012)

N_0 = 0.22 $\lambda^{2.2}$ (μ=0)

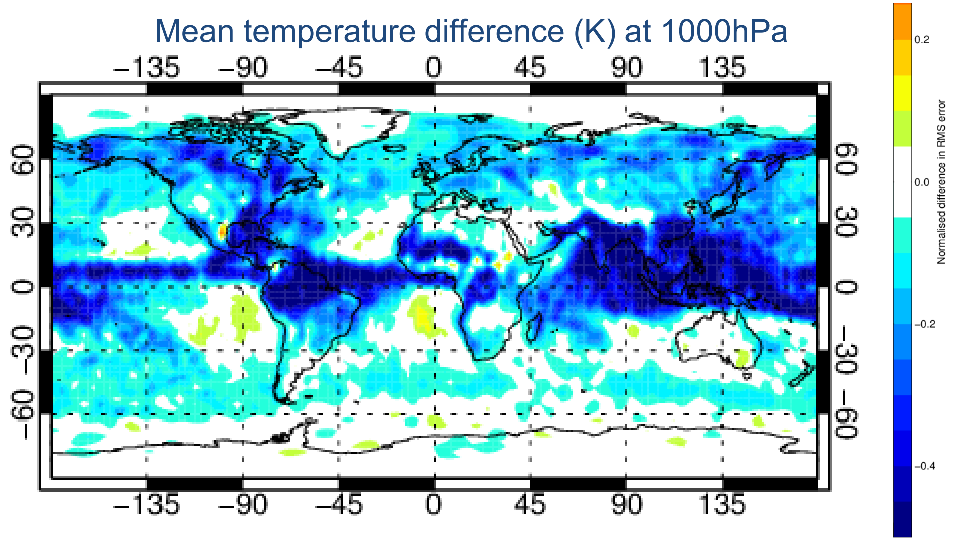
Rain evaporation rate



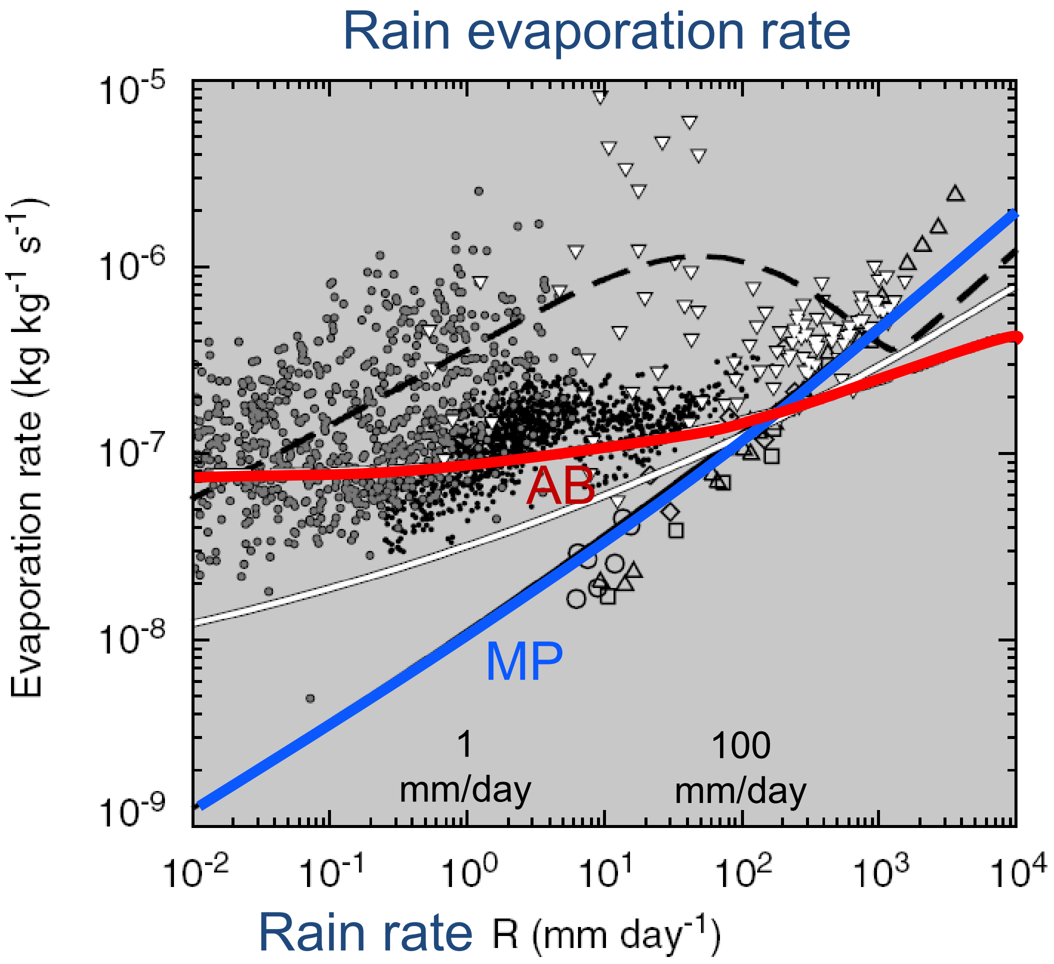
From Abel and Boutle (2012, QJRMS)

Rain drop size distribution matters for evaporation: global impacts

Impact of MP → AB PSD for stratiform **and** convective rain on low-level temperature in IFS

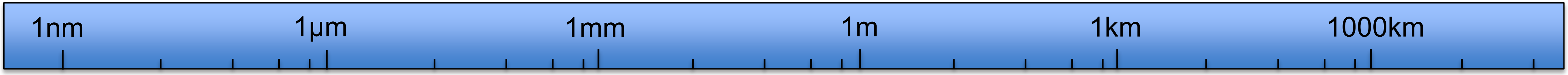

Mean temperature difference (K) at 1000hPa

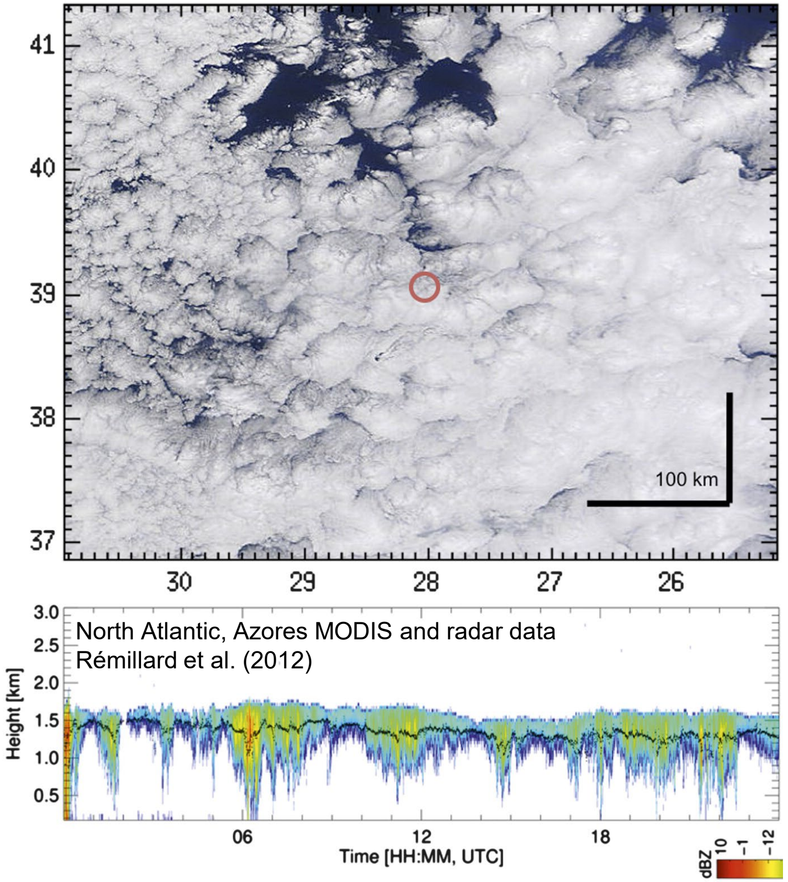
- Improved (faster) evaporation of drizzle in (marine) stratocumulus and therefore small warming near surface
- But significant (0.5K) near-surface cooling in heavier rain (degradation – too much evaporation)
- Affects stability, tropical convection, global circulation
- Wouldn't make this change in the model but it highlights importance of getting rain PSD right across different regimes


Rain evaporation rate

From Abel and Boutle (2012, QJRMS)

Examples of cloud and precipitation parametrization at different scales:

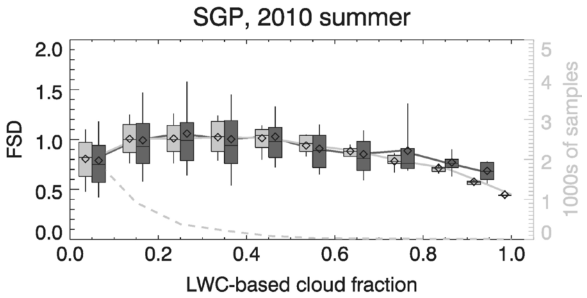


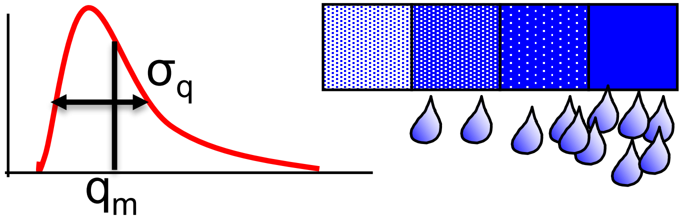


North Atlantic, Azores MODIS and radar data
Rémillard et al. (2012)

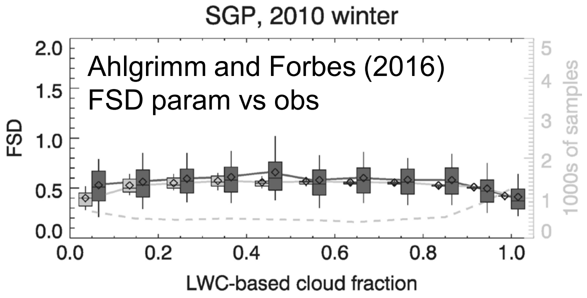
(3) In-cloud condensate heterogeneity

- Subgrid cloud and precipitation heterogeneity affects radiation and microphysics
- Can be represented diagnostically by an enhancement factor to the autoconversion rate, or predicted by a PDF scheme
- Eg. Boutle (2014), Ahlgrimm and Forbes (2016) represent with a fractional standard deviation of LWC
FSD = σ_q/q_m = stdev/mean





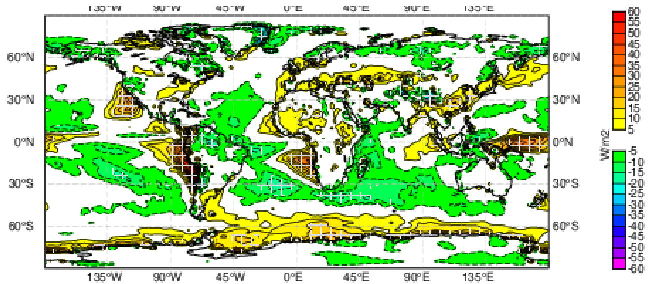
Autoconversion/Accretion



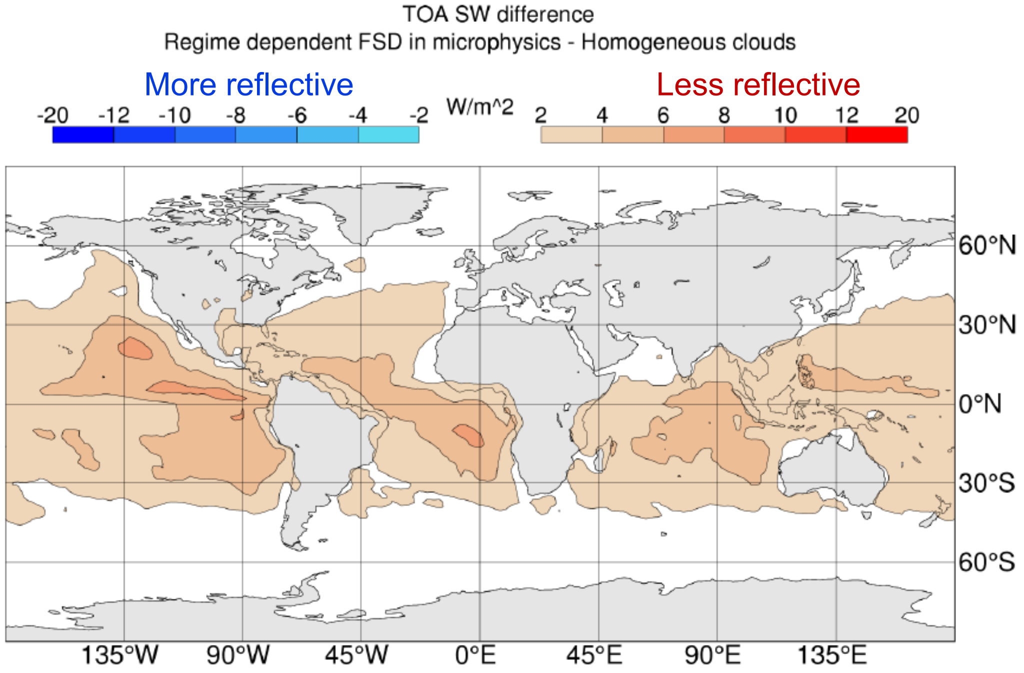
Ahlgrimm and Forbes (2016)
FSD param vs obs

Representing in-cloud sub-grid heterogeneity of cloud/precipitation; global impacts

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



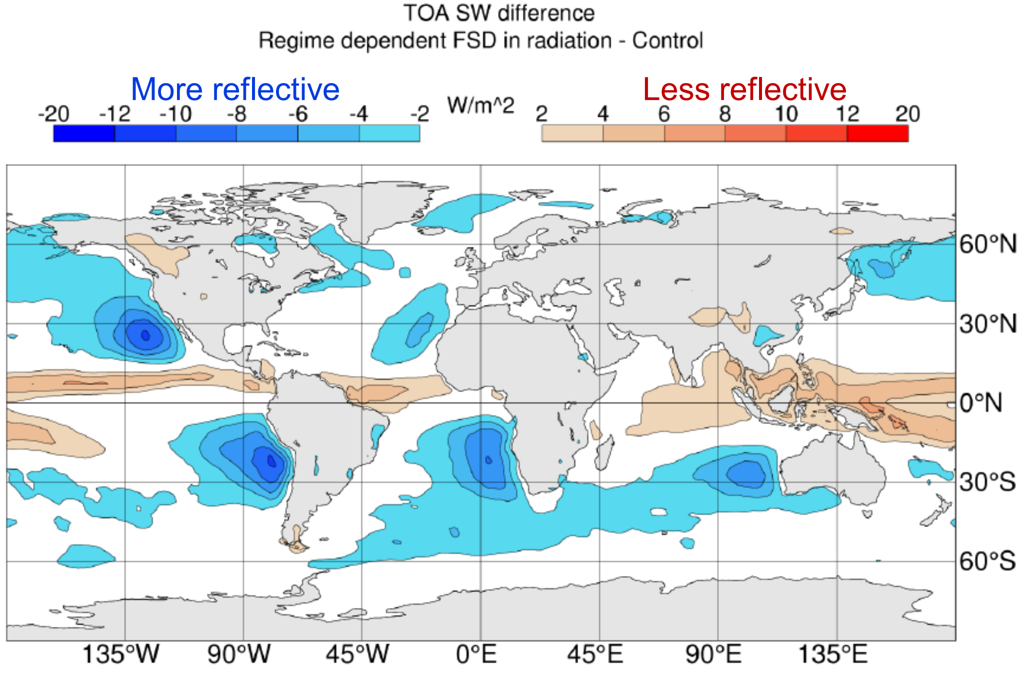
Impact of subgrid-heterogeneity in microphysics scheme


TOA SW difference

Regime dependent FSD in microphysics - Homogeneous clouds

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

Impact of subgrid-heterogeneity in radiation scheme

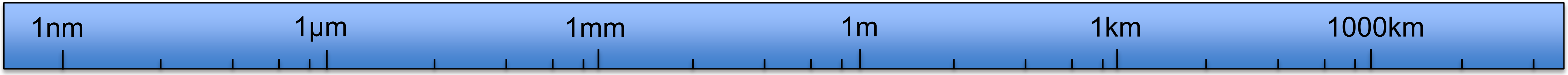

TOA SW difference

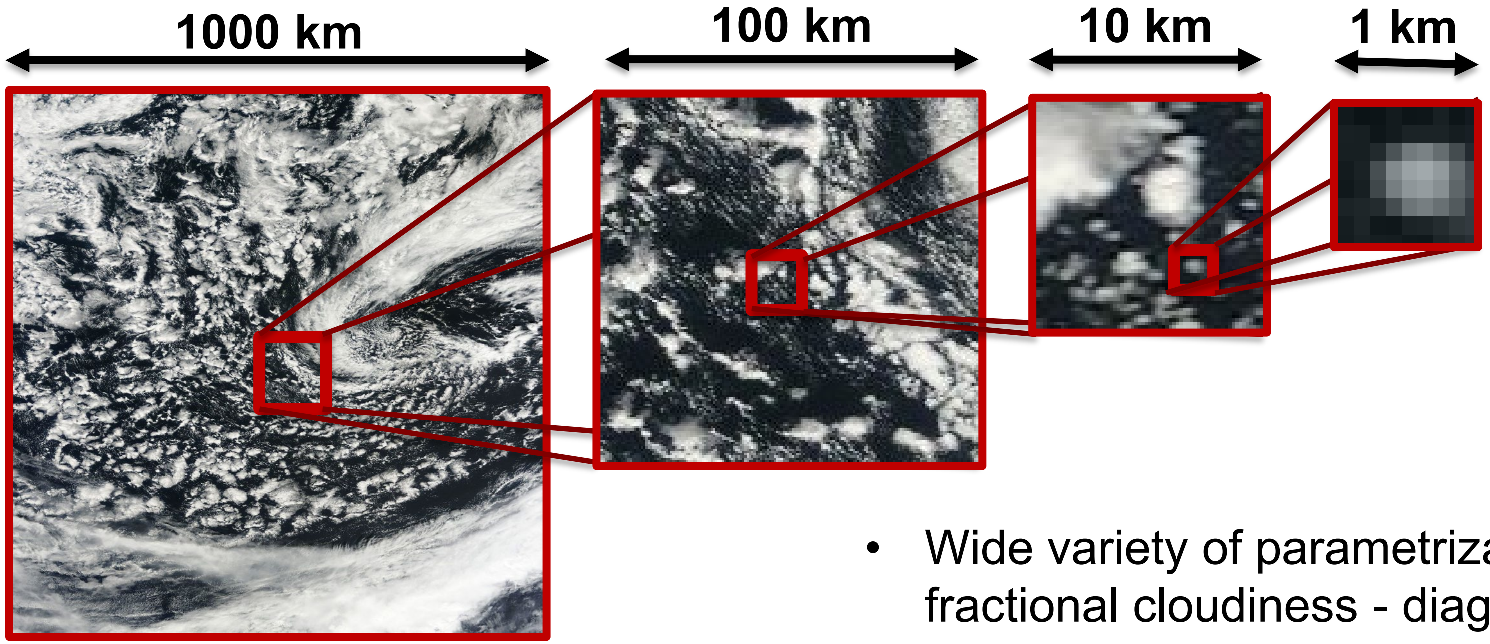
Regime dependent FSD in radiation - Control

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

Maike Ahlgrimm

Examples of cloud and precipitation parametrization at different scales:

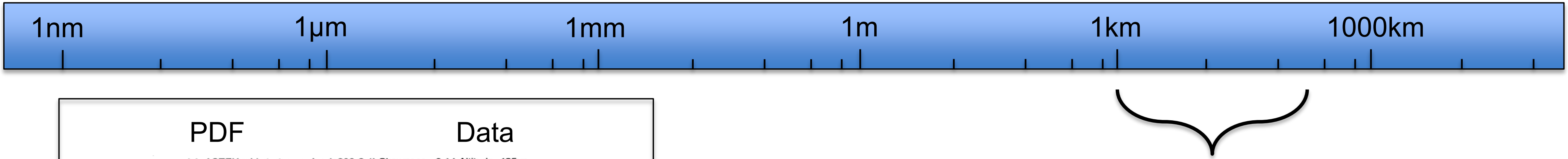


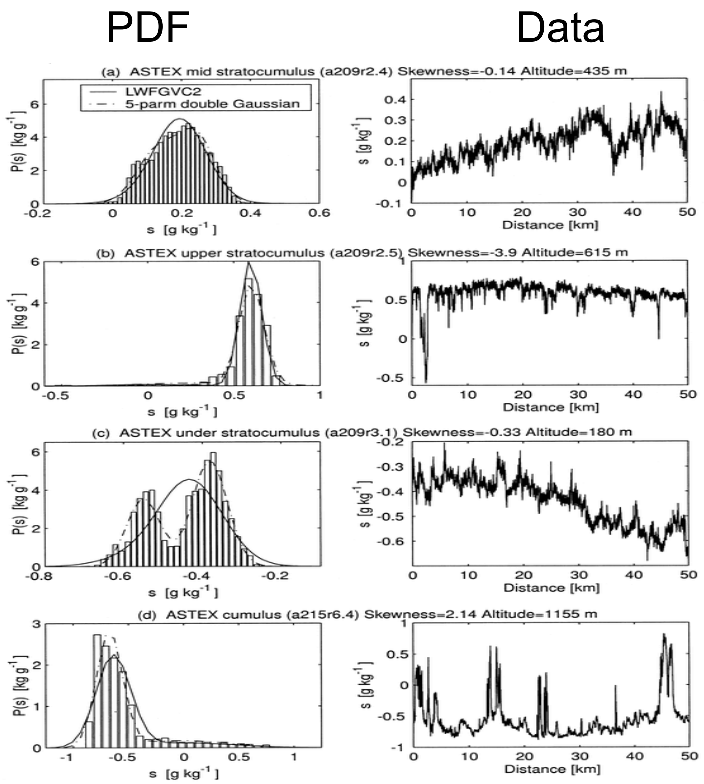


(4) subgrid-scale cloud fraction

- Wide variety of parametrization schemes to represent sub-grid fractional cloudiness - diagnostic or prognostic
- Dependencies on relative humidity, vertical air motions, turbulence
- Can be formulated with an explicit PDF of total water variability within the grid box from which can diagnose condensate and cloud fraction

Examples of cloud and precipitation parametrization at different scales:

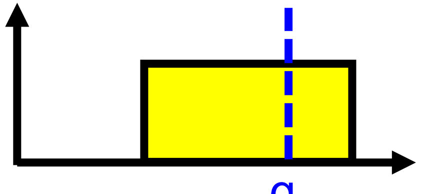




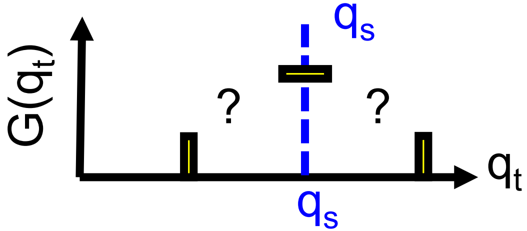
Observations of PDF of saturation deficit/excess from aircraft (Larson et al. 2001)

(4) subgrid-scale cloud fraction

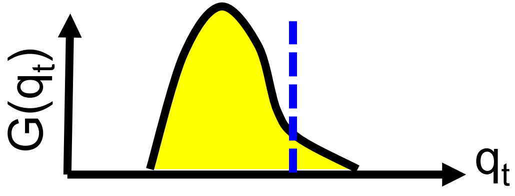
Diagnostic statistical (RH) scheme:
e.g. Sundquist (1989)



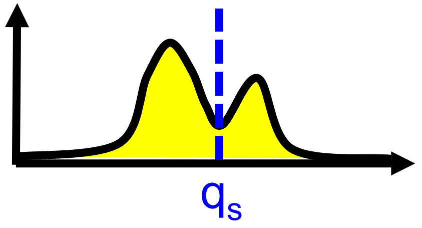
Prognostic cloud fraction scheme:
e.g. IFS (Tiedtke 1993)
MetUM (Wilson et al 08)



Prognostic PDF scheme:
e.g. Tompkins (2002) ECHAM



Prognostic PDF higher order closure scheme:
e.g. CLUBB, see talks from this Seminar:
(Machulskaya, Bastak-Duran)

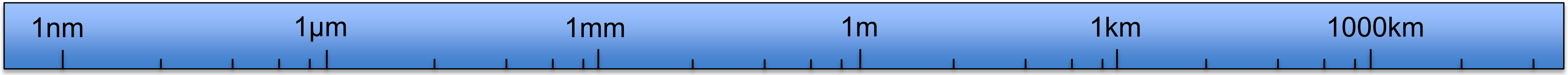


Turbulence – Convection – Cloud
parametrizations all closely linked!

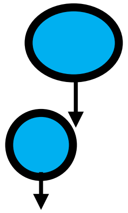
Parametrization of precipitation formation

- By explicitly representing the different scales of processes that affect the rain formation process, there is hope to better define uncertainties and sensitivities

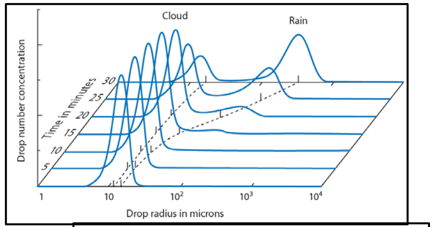
$$R' = a\bar{L}^b \quad \Rightarrow \quad R' = \int_0^l E a L^b N^c . dL$$



1. The microphysics of the sedimentation and collision-coalescence of water particles

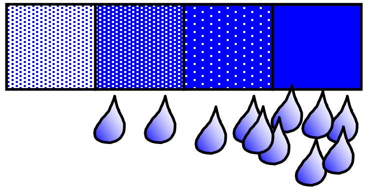


2. The combined effect of collision-coalescence integrated across the size distributions of cloud and rain drops

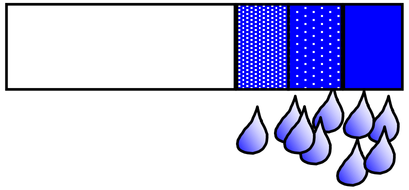


(After Berry and Reinhardt 1974)

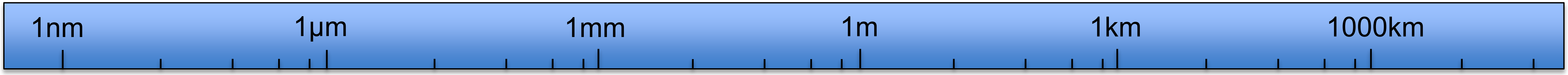
3. The effect of the variability of cloud and rain drop distributions within the cloud



4. The fractional part of the grid box that is covered by the cloud (some models use in-cloud L)



Challenge: Representing model uncertainty – stochastic perturbations



(1) Microphysics at the particle scale

(2) Particle Size Distributions

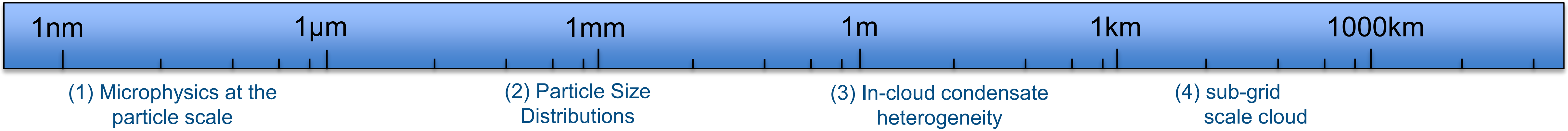
(3) In-cloud condensate heterogeneity

(4) sub-grid scale cloud

- The ECMWF operational ensemble forecast system represents model uncertainty with the **SPPT** scheme, applying **perturbations to the total physics tendency** of temperature, humidity, winds
- Currently testing **SPP** (stochastically perturbed parametrizations), applying **perturbations to separate processes/parameters** in all parametrizations, closer to the source of uncertainties (see Lang et al. 2021)
- In SPP – what to perturb? Microphysical parameter? Microphysical process? Grid-scale processes? Whole parametrization tendency? It’s a balance between computational cost (no. of perturbation choices), how well we can characterize the uncertainty, and making sure we cover all the important processes
- E.g. for rain evaporation, could perturb the particle size distribution or subgrid heterogeneity?
  In practice for the current SPP, simply perturb the rain evaporation rate, gives direct control over the latent heating and represents all the uncertainties in this process
- In the future? Understanding uncertainty of processes at different scales and their impacts on the model is key to improving the representation of stochastic perturbations

SPPT: Buizza et al. (1999), Leutbecher et al. (2017), Lock et al. (2019)
SPP: Ollinaho et al. (2017, QJRMS), Lang et al. (2021, QJRMS)

Challenge: Constraining microphysics (globally?) with observations



(1) Microphysics at the particle scale

(2) Particle Size Distributions

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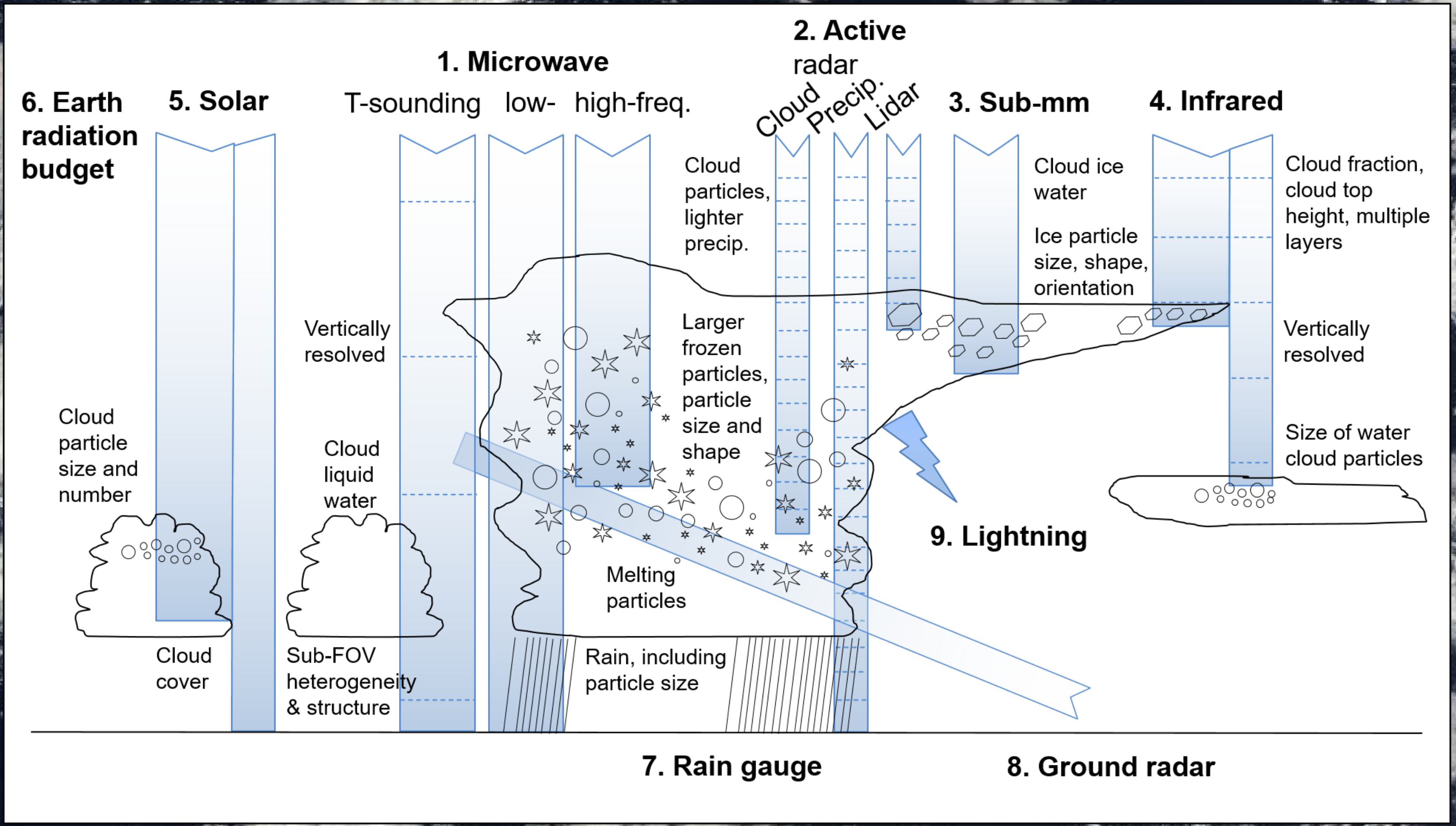
- Constrain cloud/precip properties at different scales

- Use synergy of obs (e.g. diff frequencies)

- Cloud effective radius
- Cloud phase
- Ice particle habit
- Precipitation particles
- LWP, IWP
- Spatial PDFs
- Vertical velocities (INCUS)



Challenges for global modelling of cloud and precipitation across scales

1. Improving the **skill and realism** of global NWP across timescales
2. Increasing global model resolution **towards the km-scale**
3. Representing **model uncertainty** for ensemble prediction
4. Constraining models with **observations** globally

We are making progress by

- understanding the processes **and** their uncertainties
- constraining with observations where we can
- and consistently representing these in our parametrizations

across the different scales

→ seamless prediction from 100km to 1km