Evaluation and improvement of *mixed-phase* cloud schemes using radar and lidar observations

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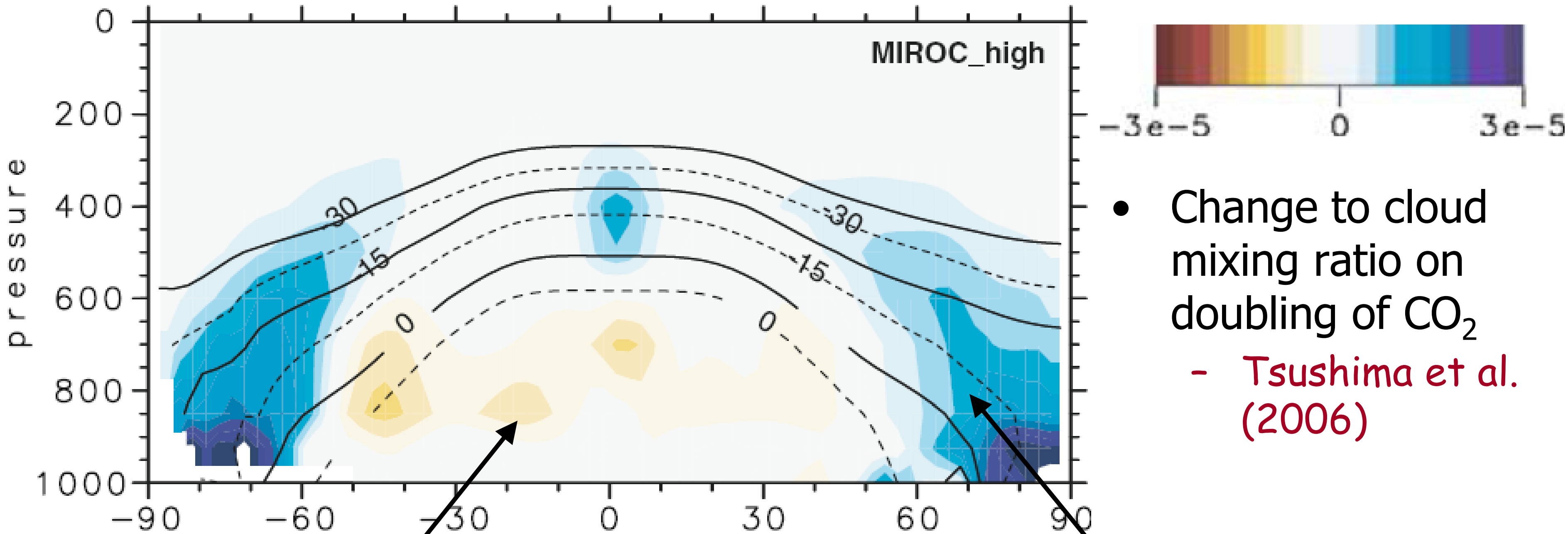
Overview

- Why are mixed-phase clouds so poorly captured in GCMs?
  - These clouds are potentially a key negative feedback for climate
  - Getting these clouds right requires the correct specification of turbulent mixing, radiation, microphysics, fall speed, sub-grid structure etc.
- What is the *minimum* complexity capable of capturing mixed-phase?
  - Do we need prognostic ice nuclei?
- *Vertical* resolution is a key issue for representing thin liquid layers
  - Can we devise a scale-independent parameterization?
- Use a 1D model and long-term cloud radar and lidar observations
  - Easy to perform many sensitivity studies to changed physics

Mixed-phase cloud radiative feedback



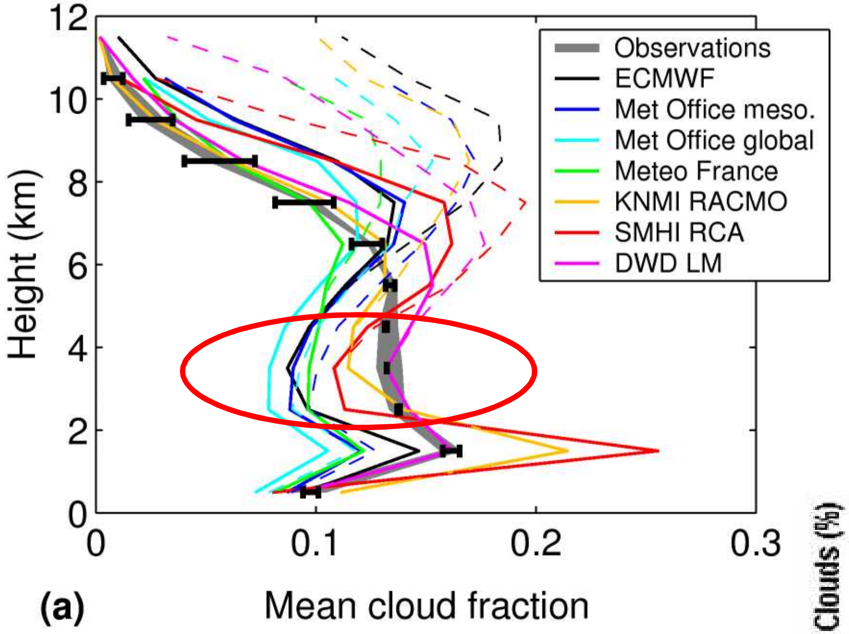
- Change to cloud mixing ratio on doubling of CO_2
  - Tsushima et al. (2006)

- Decrease in subtropical stratocumulus
  - Lower albedo -> positive feedback on climate

- Increase in polar boundary-layer and mid-latitude mid-level clouds
  - Clouds more likely to be liquid phase: lower fall speed so more persistent
  - Higher albedo -> negative climate feedback (Mitchell et al. 1989)
  - *Depends on questionable model physics!*

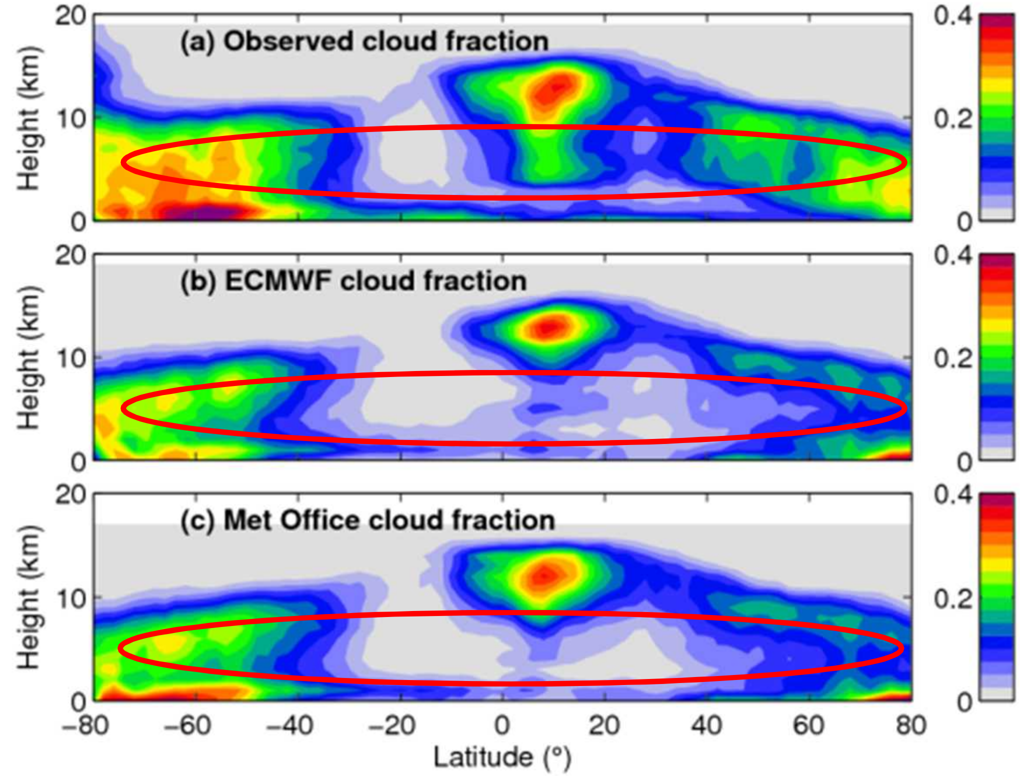
How well do models capture mid-level clouds?

- Ground-based radar and lidar (Illingworth, Hogan et al. 2007)

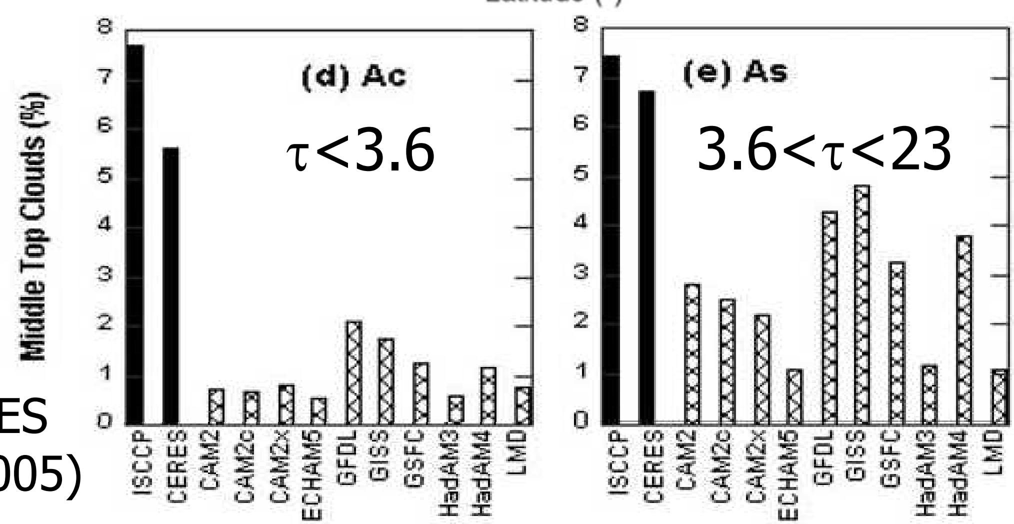


Models miss at least a third of mid-level clouds

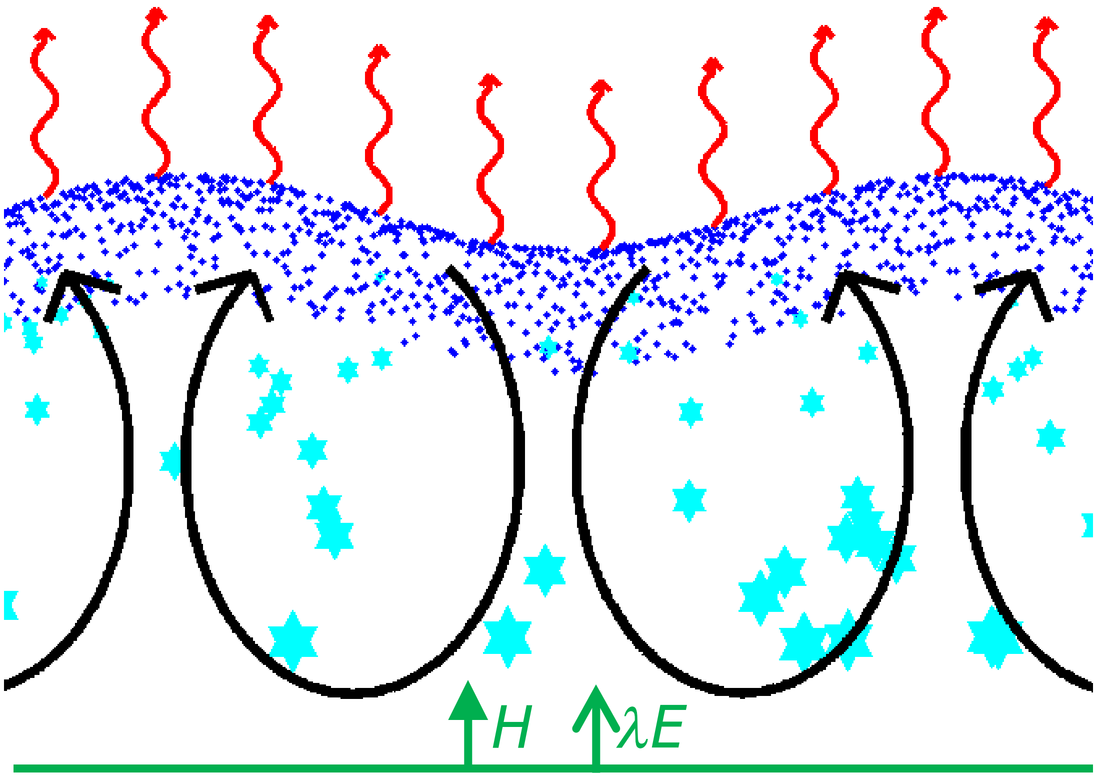
- CloudSat & Calipso (Hogan, Stein, Garcon, Delanoe, Forbes, Bodas-Salcedo, in prep.)



- ISCCP and CERES (Zhang et al. 2005)



Important processes in altocumulus

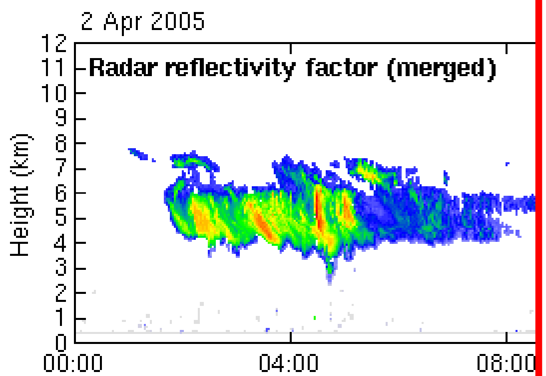


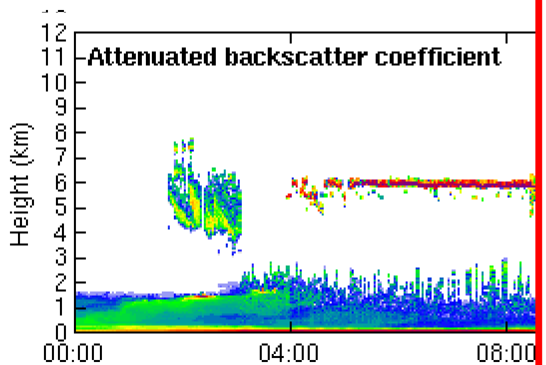
- Longwave cloud-top cooling
- Supercooled droplets form
- Cooling induces upside-down convective mixing
- Some droplets freeze
- Ice particles grow at expense of liquid by Bergeron-Findeisen
- Ice particles fall out of layer
- Most previous studies (e.g. Xie et al. 2008) in Arctic: surface fluxes important

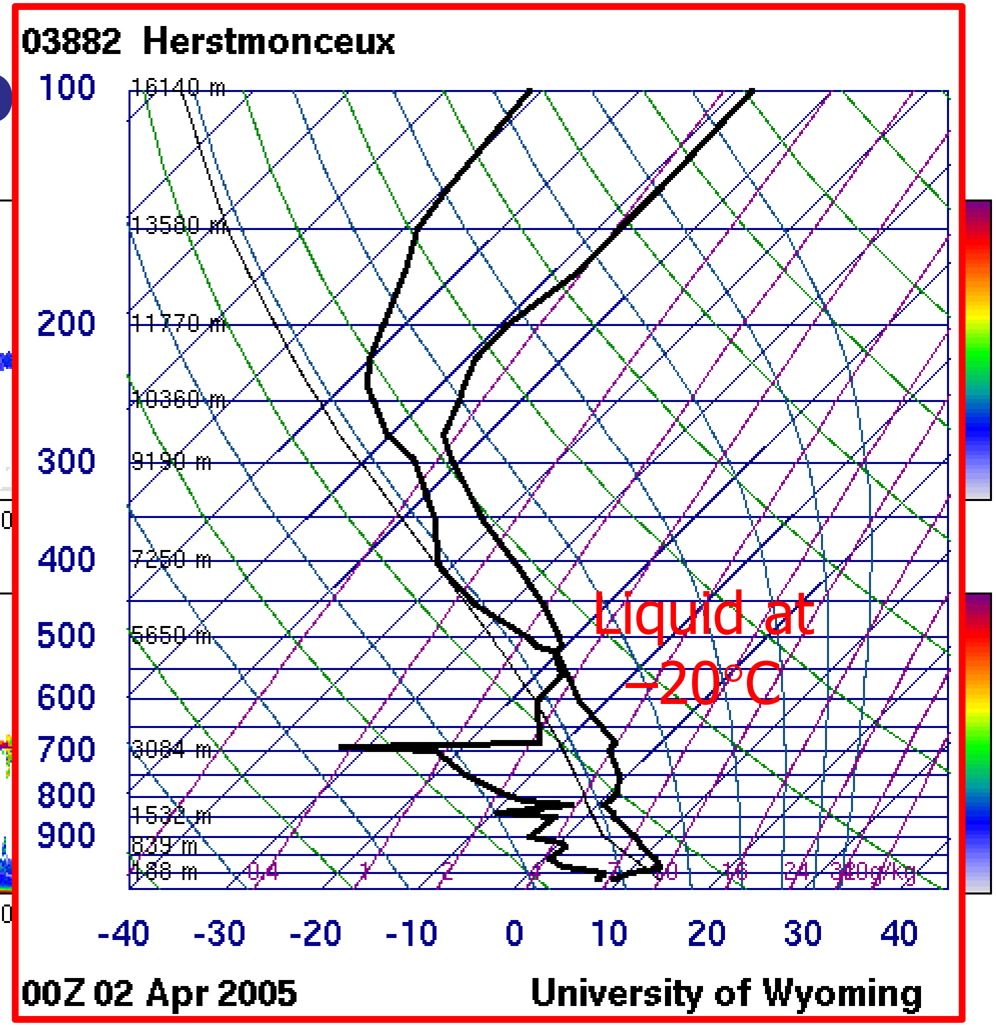
- Many models have prognostic cloud water content, and temperature-dependent ice/liquid split, with less liquid at colder temperatures
  - Impossible to represent altocumulus clouds properly!
- Newer models have separate prognostic ice and liquid mixing ratios
  - Are they better at mixed-phase clouds?

Observations of lo

- Radar reflectivity (large particles)
- Lidar backscatter (small particles)

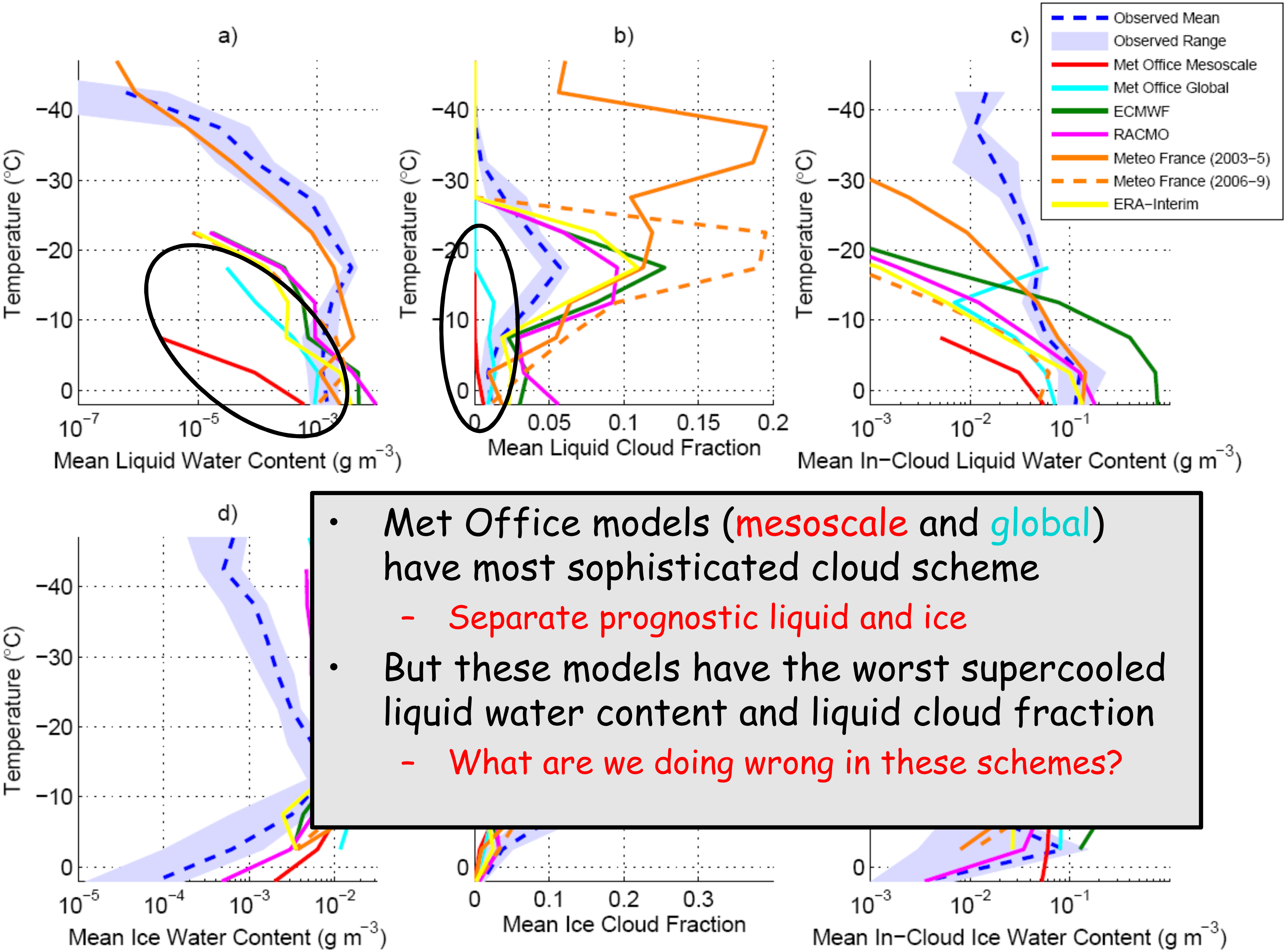






- Estimate ice water content from radar reflectivity factor and temperature
- Estimate liquid water content from microwave radiometer using scaled adiabatic method

21 altocumulus days at Chilbolton



- Met Office models (mesoscale and global) have most sophisticated cloud scheme
  - Separate prognostic liquid and ice
- But these models have the worst supercooled liquid water content and liquid cloud fraction
  - What are we doing wrong in these schemes?

1D "EMPIRE" model

- Single column model
- High vertical resolution
  - Default: Δz = 50m
- Five prognostic variables
  - u, v, θ_l, q_t and q_i
- Default: follows Met Office model
  - Wilson & Ballard microphysics
  - Smith (1990) sub-grid q_t
  - Local and non-local mixing
  - Explicit cloud-top entrainment

- Variables conserved under moist adiabatic processes:
- Total water (vapour plus liquid):

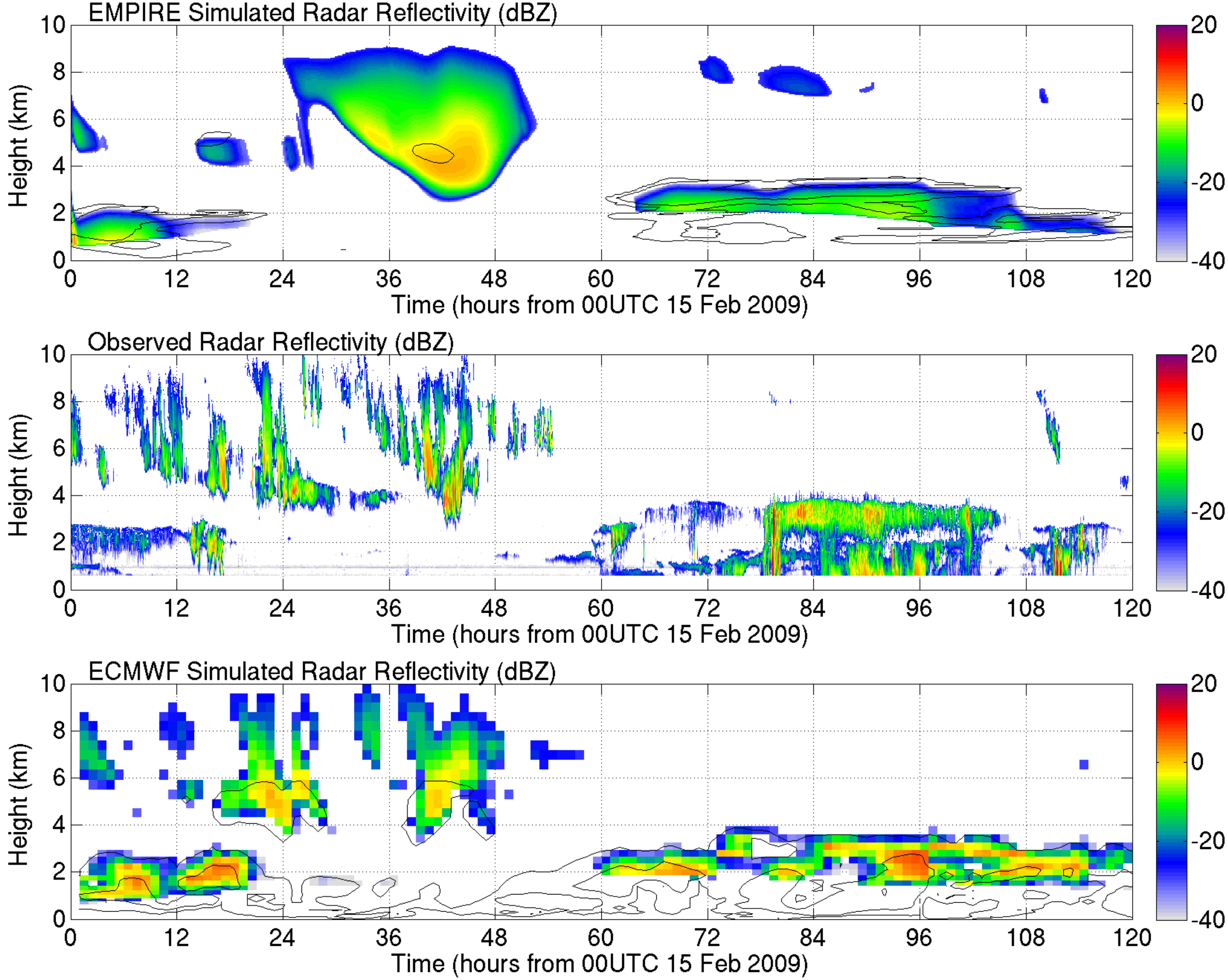
$$q_t = q + q_l$$

- Liquid water potential temperature

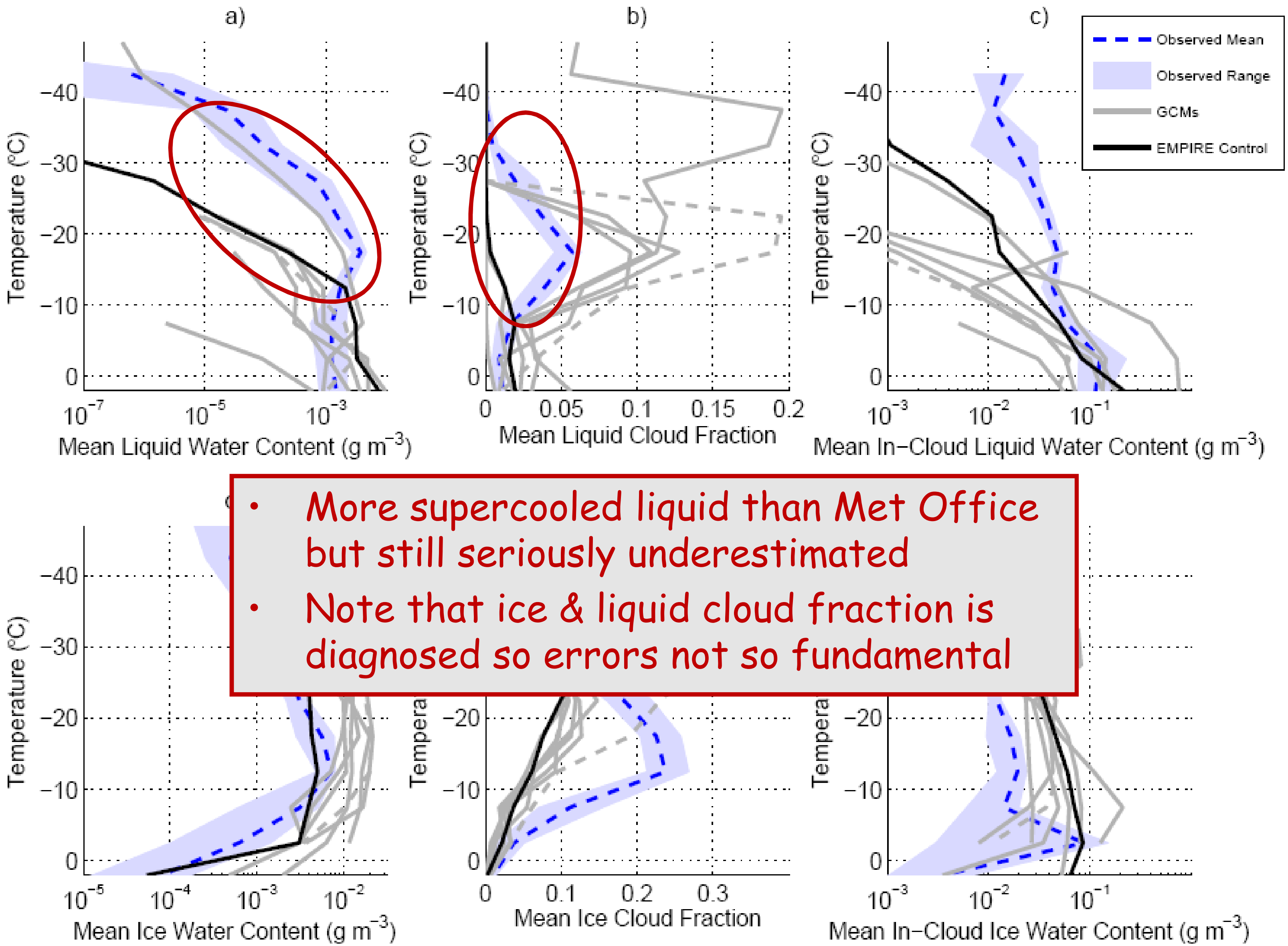
$$\theta_l = \theta - \frac{\theta}{T}\frac{L}{C_p}q_l$$

- Frequent radiation updates (Edwards & Slingo scheme)
- Advective forcing using ERA-Interim
- Flexible: very easy to try different parameterization schemes
  - Coded in matlab
- Each configuration compared to set of 21 Chilbolton altocumulus days

EMPIRE model simulations



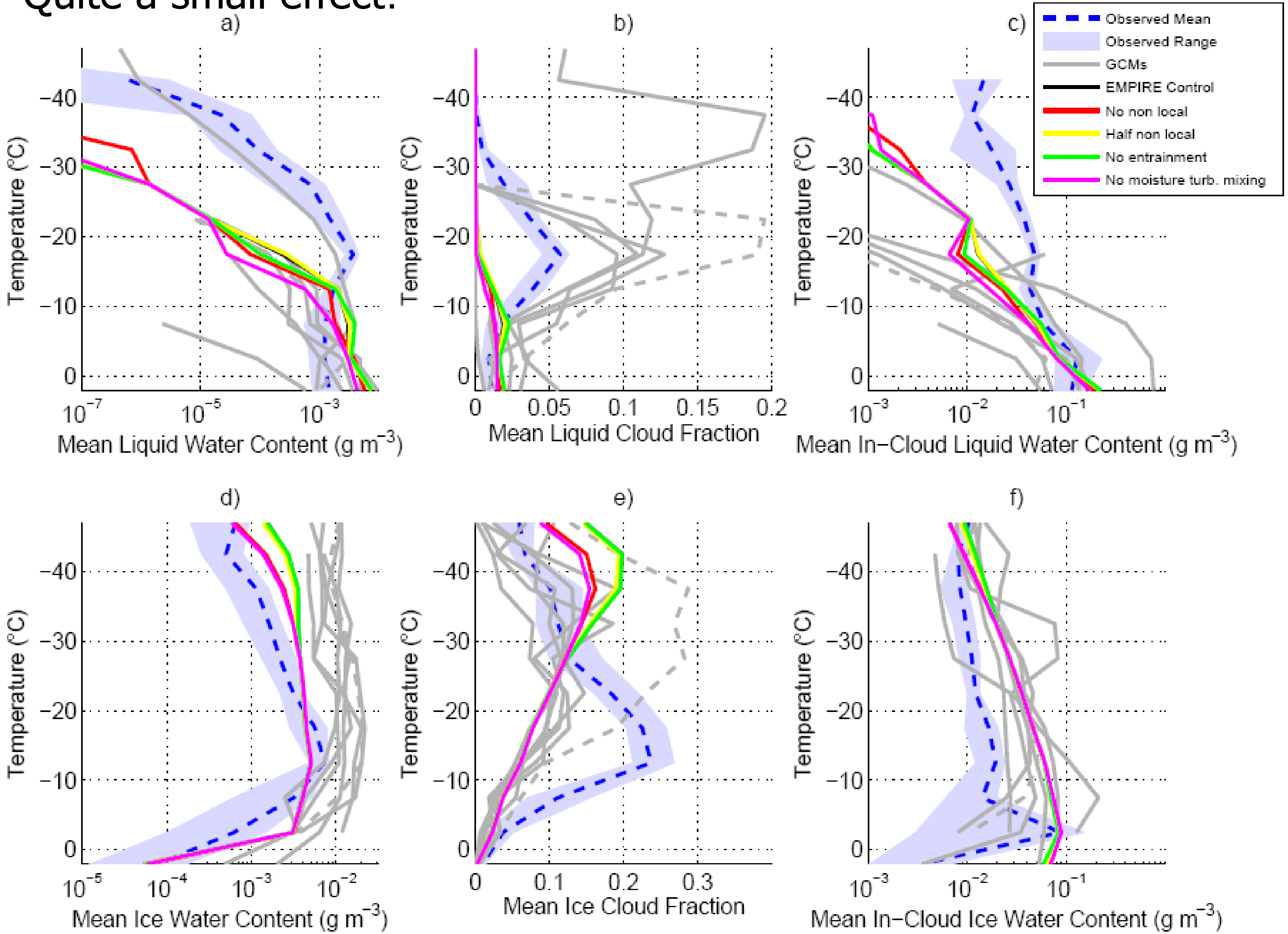
Evaluation of EMPIRE control model



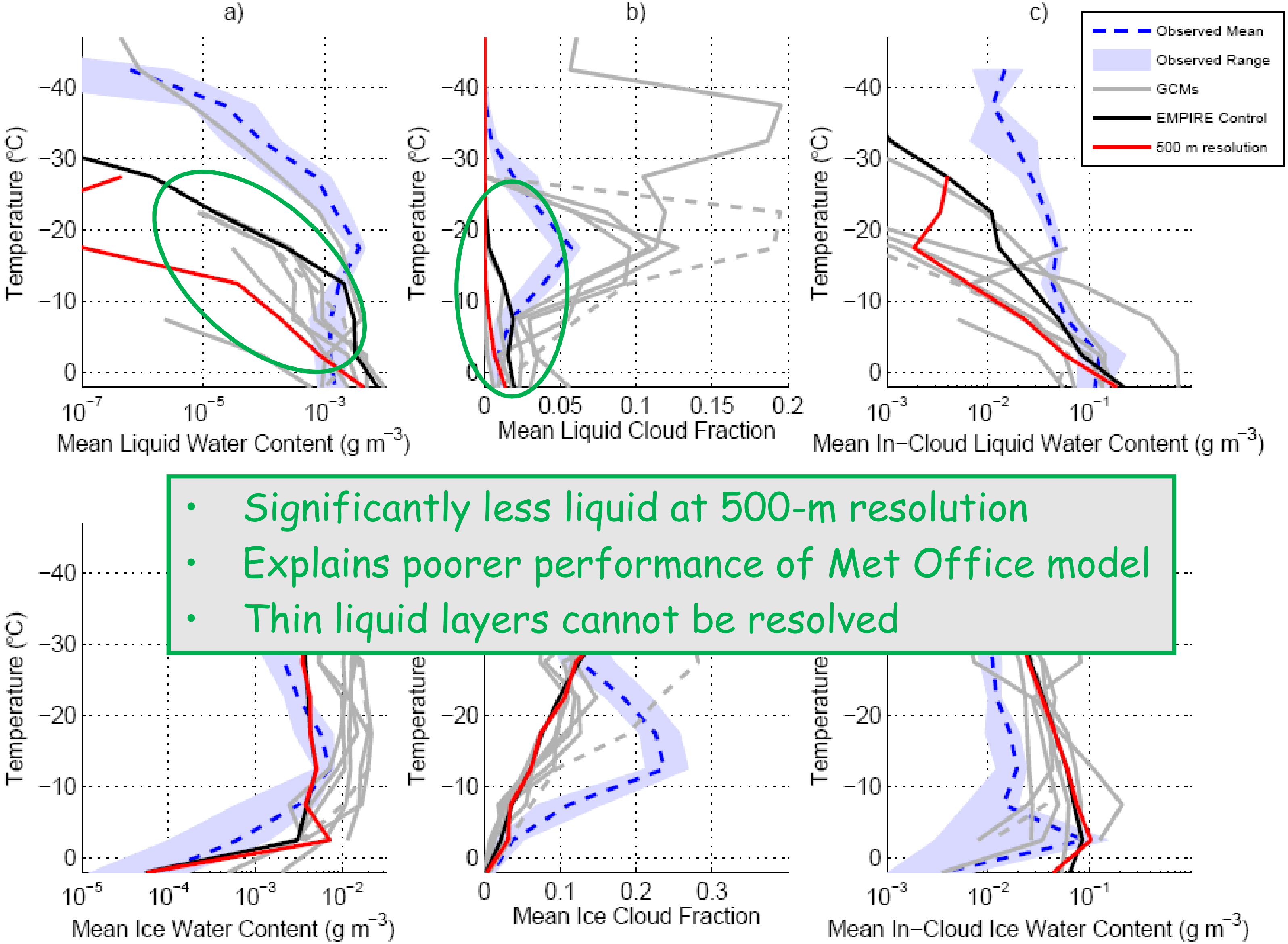
- More supercooled liquid than Met Office but still seriously underestimated
- Note that ice & liquid cloud fraction is diagnosed so errors not so fundamental

Effect of turbulent mixing scheme

- Quite a small effect!

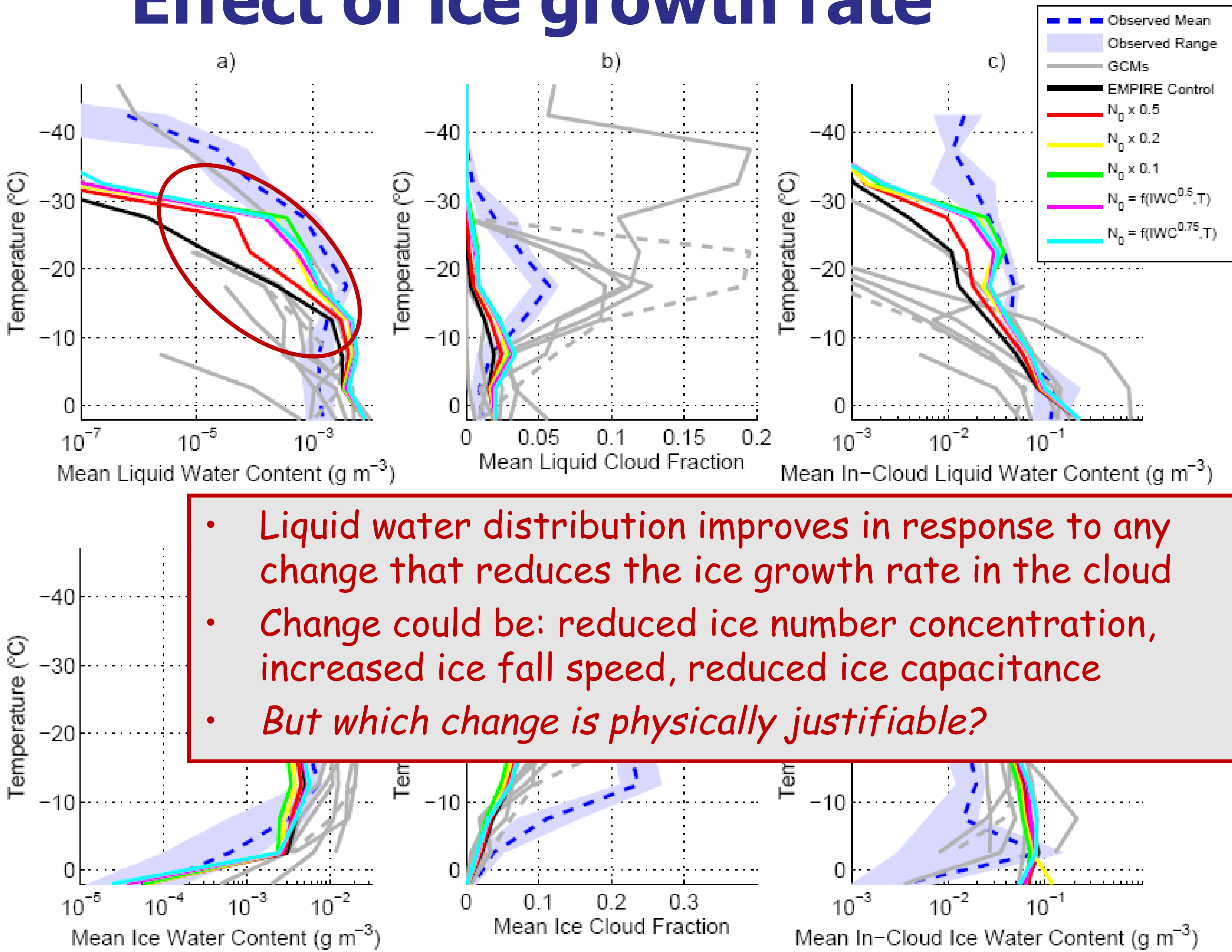


Effect of vertical resolution



- Significantly less liquid at 500-m resolution
- Explains poorer performance of Met Office model
- Thin liquid layers cannot be resolved

Effect of ice growth rate



- Liquid water distribution improves in response to any change that reduces the ice growth rate in the cloud
- Change could be: reduced ice number concentration, increased ice fall speed, reduced ice capacitance
- *But which change is physically justifiable?*

Summary of sensitivity tests

Main model sensitivities appear to be:

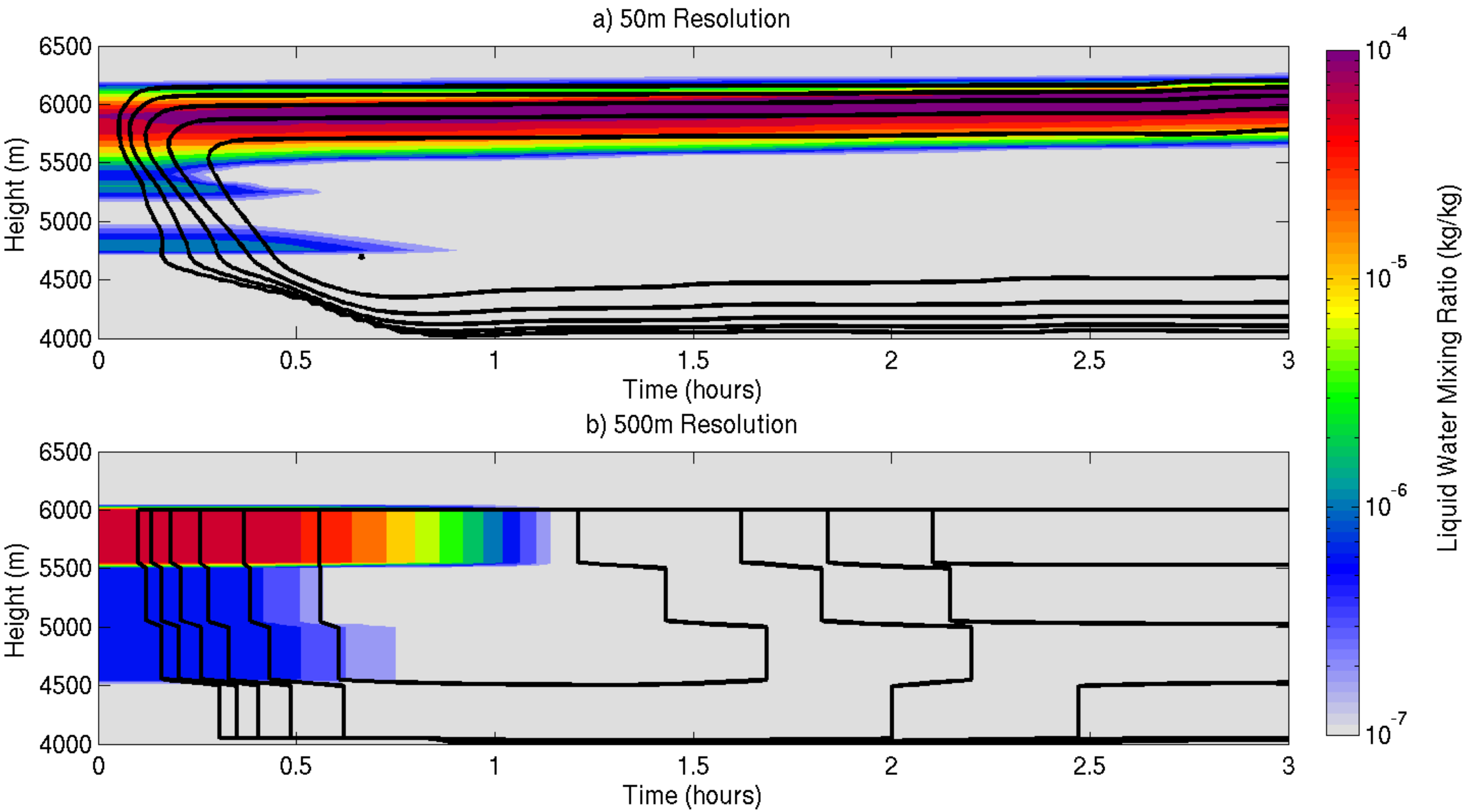
- Vertical resolution
  - Can we parameterize the sub-grid vertical distribution to get the same result in the high and low resolution models?
- Ice growth rate
  - Is there something wrong with the size distribution assumed in models that causes too high an ice growth rate when the ice water content is small?
- Ice cloud fraction
  - In most models this is a function of ice mixing ratio and temperature
  - We have found from Cloudnet observations that the temperature dependence is unnecessary, and that this significantly improves the ice cloud fraction in clouds warmer than –30°C (not shown)

Apparently less important:

- Sub-grid mixing specification, radiation timestep (surprising!)

Resolution dependence: idealised simulation

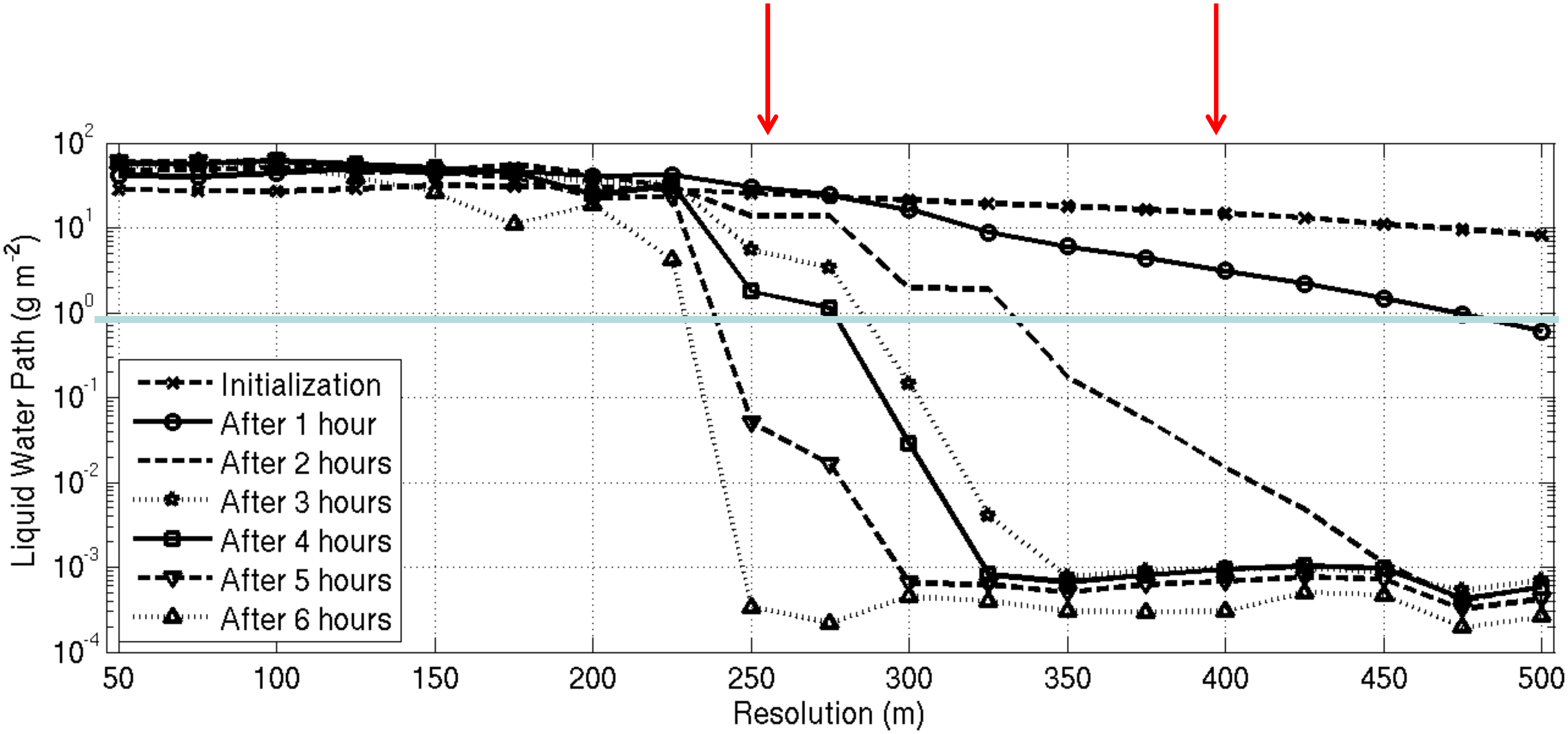
•Liquid Ice



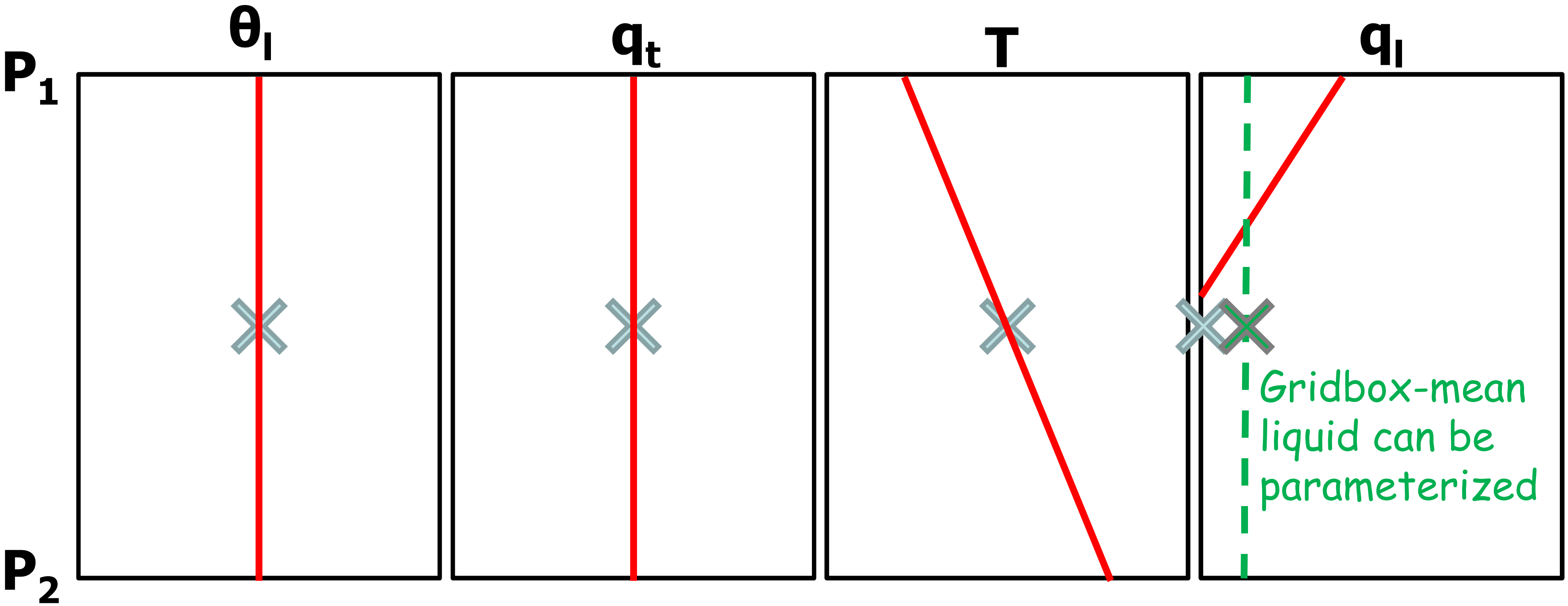
Resolution dependence

Best NWP resolution

Typical NWP resolution



Effect 1: thin clouds can be missed



- Consider a 500-m model level at the top of an altocumulus cloud
- Consider prognostic variables θ_l and q_t that lead to $q_l = 0$
  - But layer is well mixed which means that even though prognostic variables are constant with height, T decreases significantly in layer
  - *Therefore a liquid cloud may still be present at the top of the layer*

Effect 2: Ice growth too high at cloud top

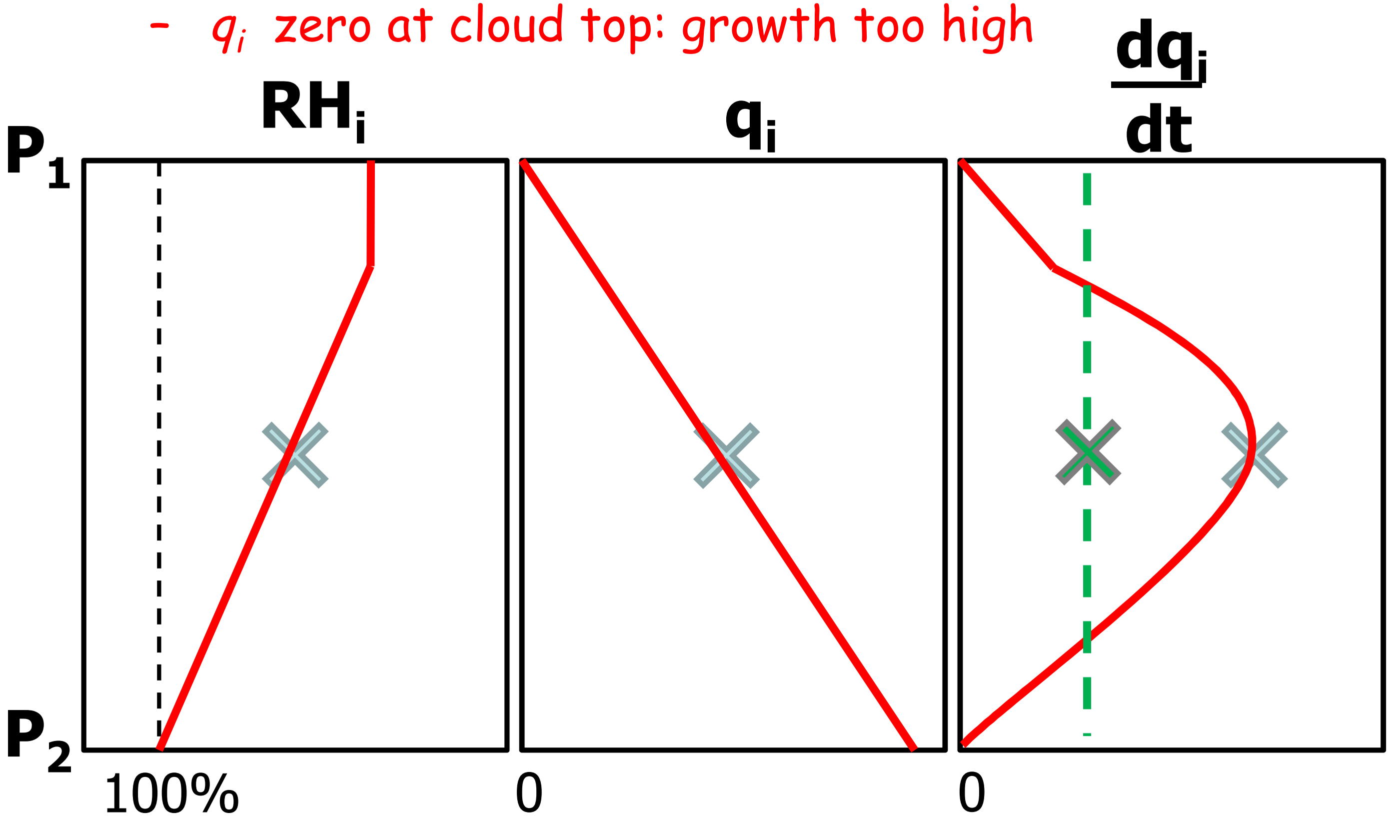
- Diffusional growth:

$$\frac{dq_i}{dt} = AD(\mathrm{RH}_i - 1) \propto q_i^{2/3}(\mathrm{RH}_i - 1)$$

q_i = ice mixing ratio, ice diameter $D \propto q_i^{2/3}$

RH_i = relative humidity with respect to ice

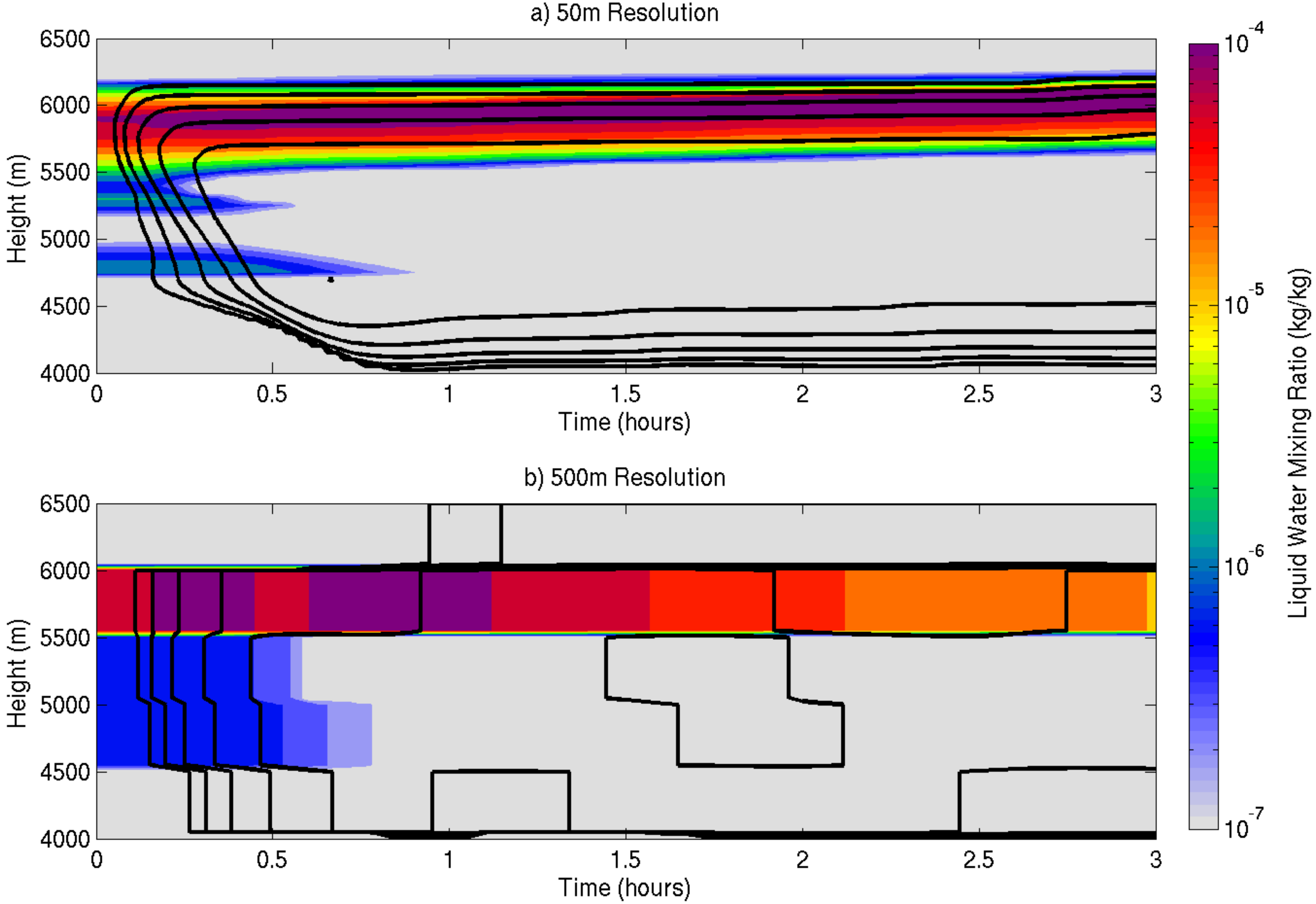
  - q_i zero at cloud top: growth too high



Assume linear q_i profile to enable gridbox-mean growth rate to be estimated: significantly lower than before

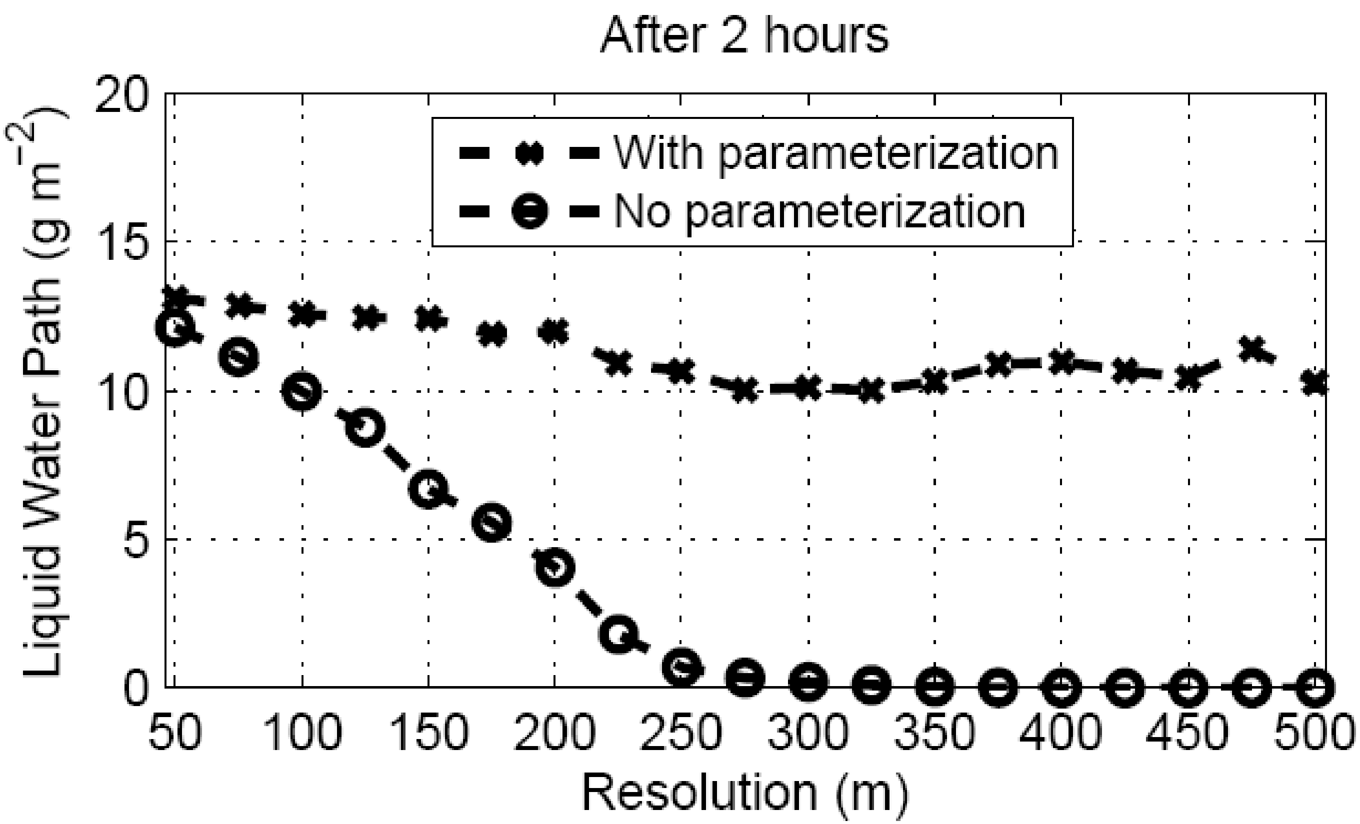
Parameterization at work

•Liquid Ice



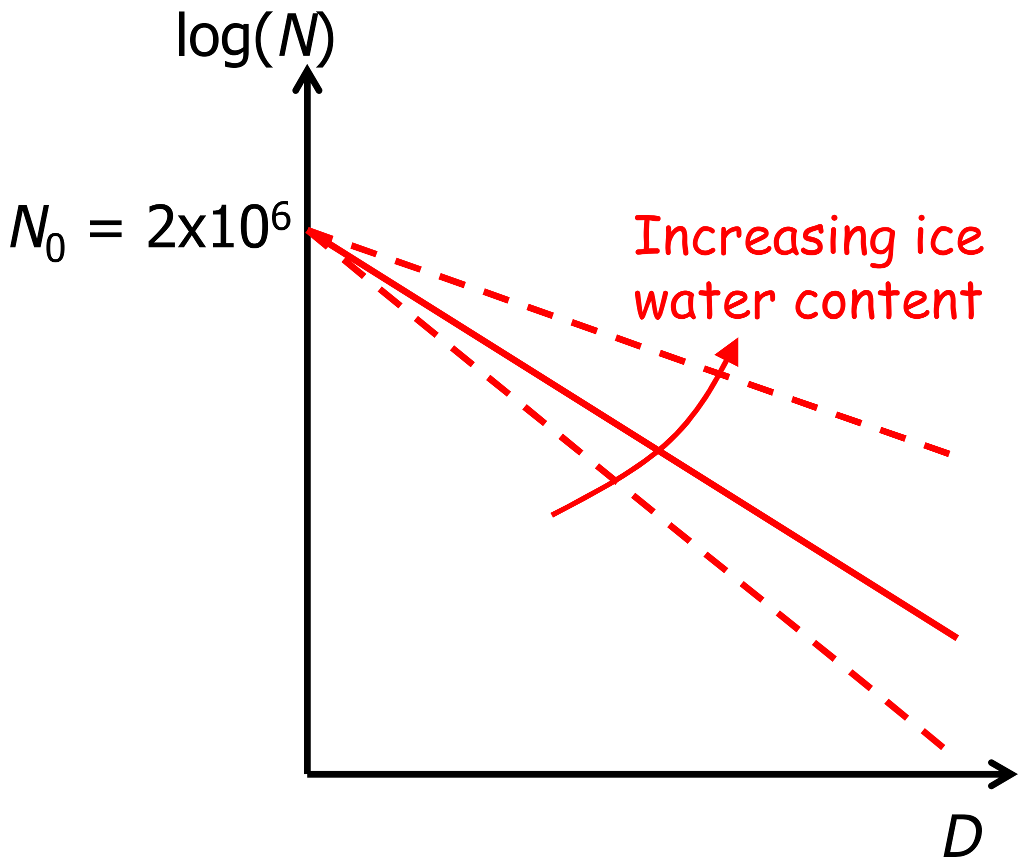
Parameterization at work

- New parameterization works well over full range of model resolutions



- Typically applied only at cloud top, which can be identified objectively

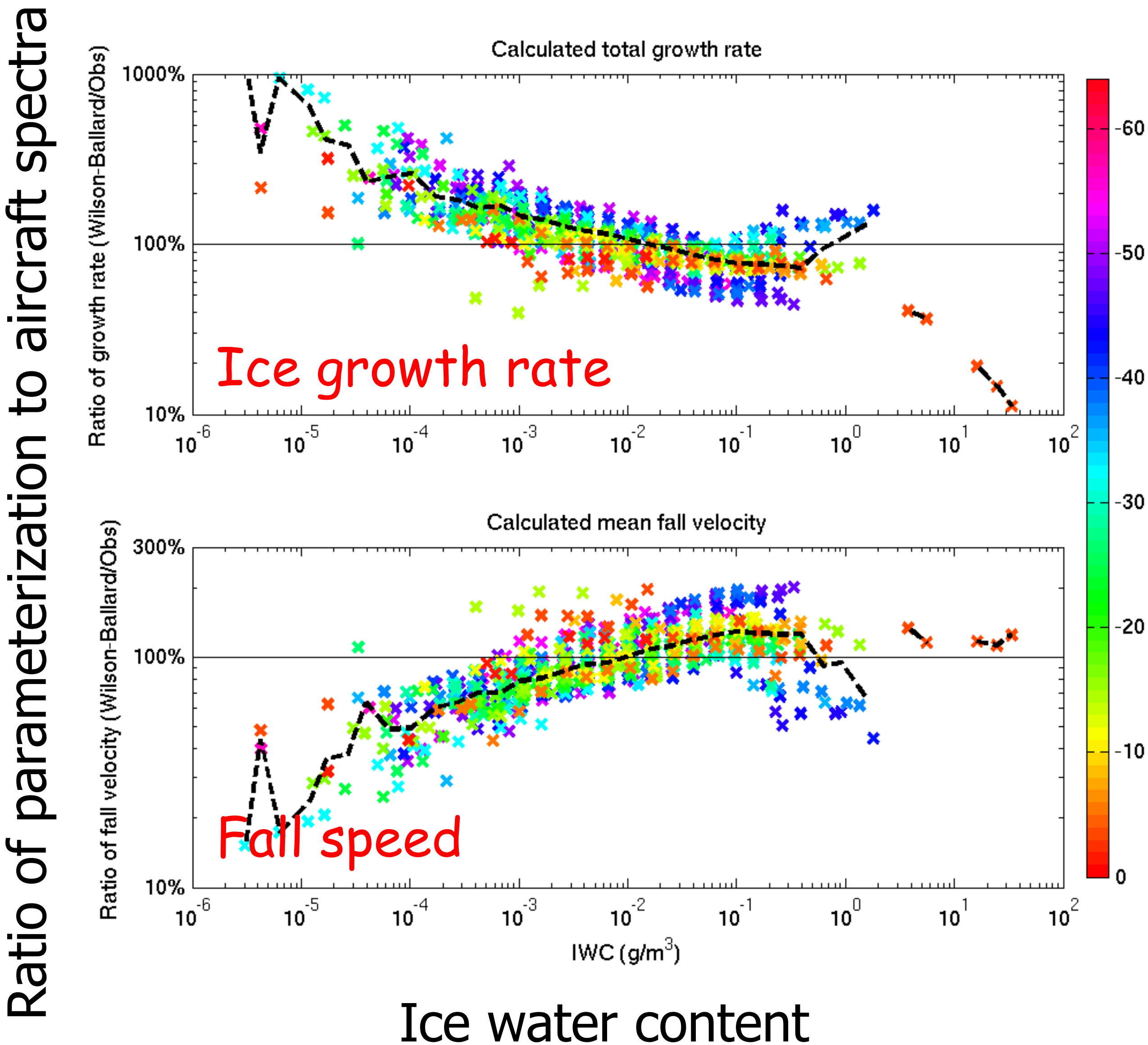
Standard ice particle size distribution

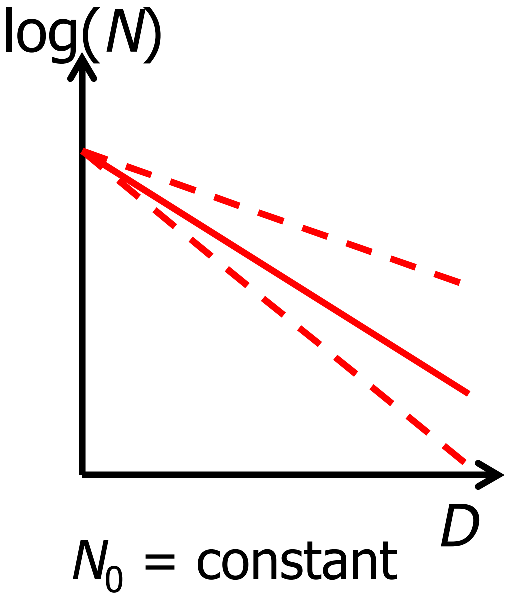


- "Marshall-Palmer" inverse exponential used in all situations
- Simply adjust slope to match ice water content
  - Wilson and Ballard scheme used by Met Office
  - Similar schemes in many other models

- *But how does calculated growth rate versus ice water content compare to calculations from aircraft spectra?*

Parameterized growth rates

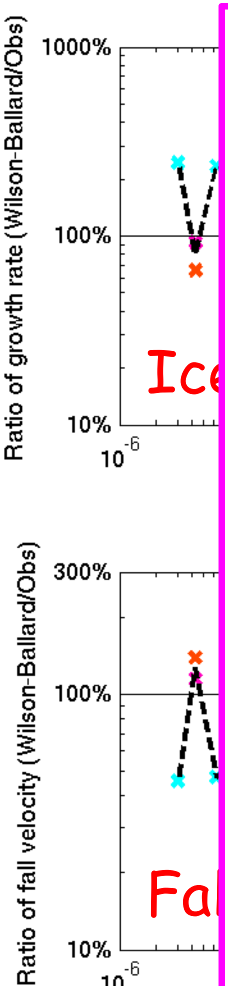


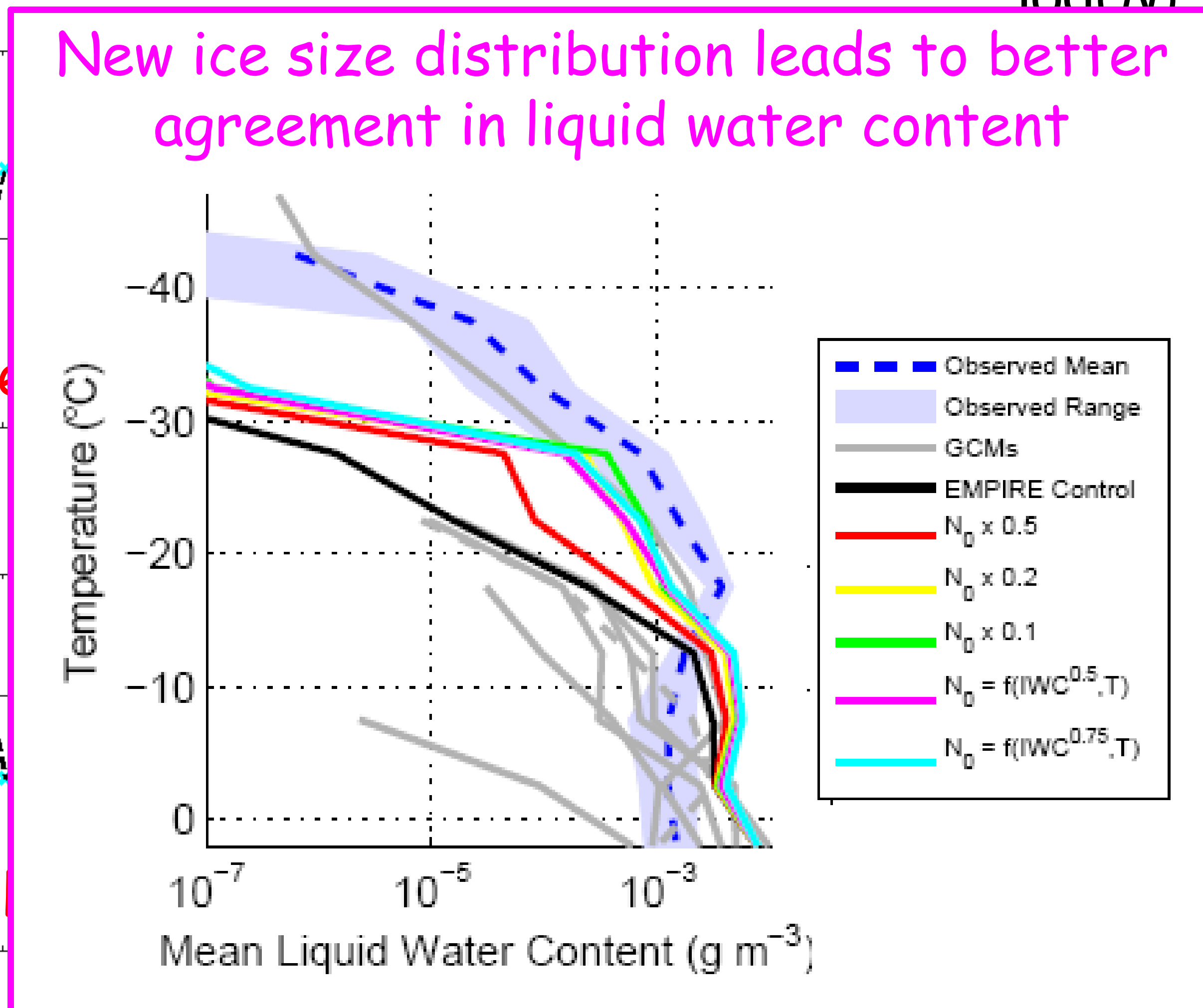


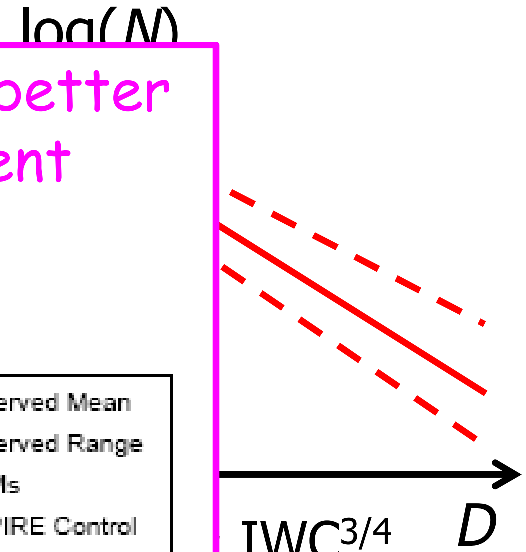
- Ice clouds with low water content:
  - Ice growth rate too high
  - Fall speed too low
- Liquid clouds depleted too quickly!

Adjusted growth rates

Ratio of parameterization to aircraft spectra







Ice water content

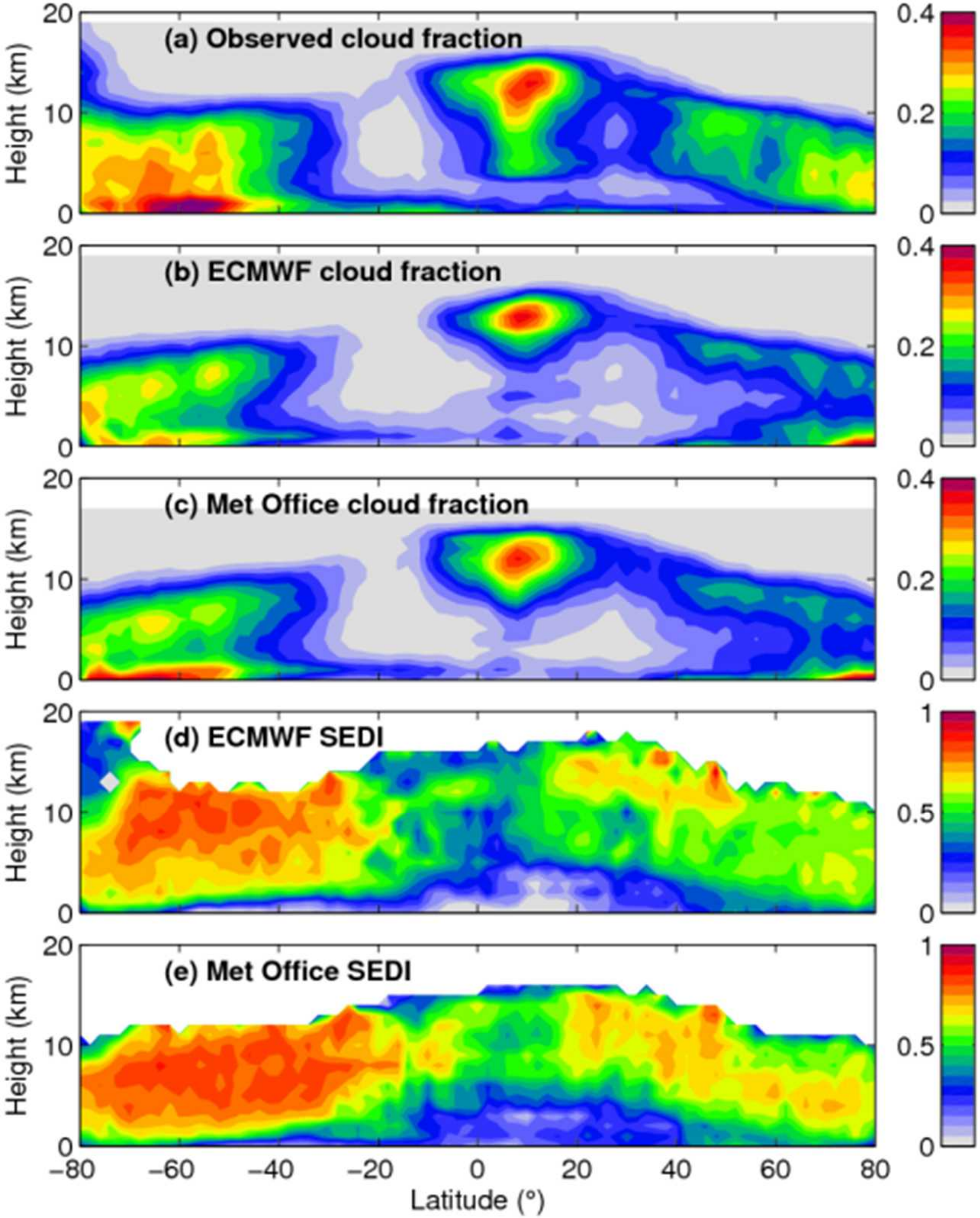
e and Hogan
suggest N_0
for low water
t

h better
wth rate and
speed

- *Need to account for ice shattering!*

Conclusions

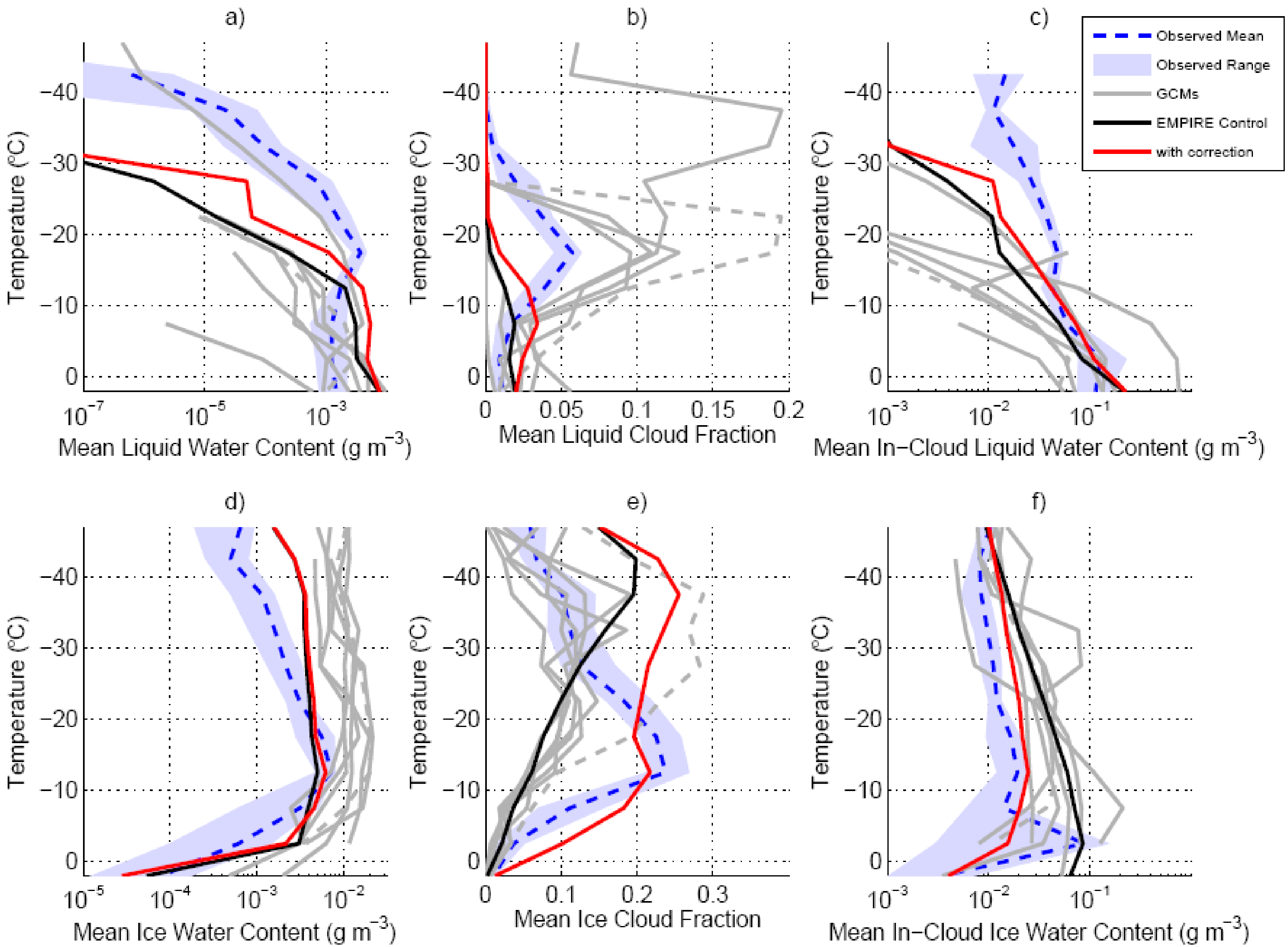
- Why are mixed-phase clouds so poorly captured in GCMs?
  - Two key effects that lead to ice growth too fast at cloud top
- Sub-grid structure in the *vertical*
  - Strong resolution dependence near cloud top; can be parameterized to allow liquid layers that only partially fill the layer vertically
  - We have parameterized effect on liquid occurrence and ice growth
- Error in assumed ice size distribution
  - More realistic size distribution has fewer, larger crystals at cloud top
  - Lower ice growth and faster fall speeds so liquid depleted more slowly
  - Need to check with aircraft data free of shattering
- Ground-based radar and lidar observations very useful
  - Can develop GCM-type schemes without LES as an intermediary
- Implications for large scale models
  - *NWP:* Richard Forbes shown large surface temperature errors unless cloud-top ice growth scaled back: *now has physical basis*
  - *Climate:* urgent need to re-evaluate mixed-phase cloud contribution to climate sensitivity using models with better physics



Model skill

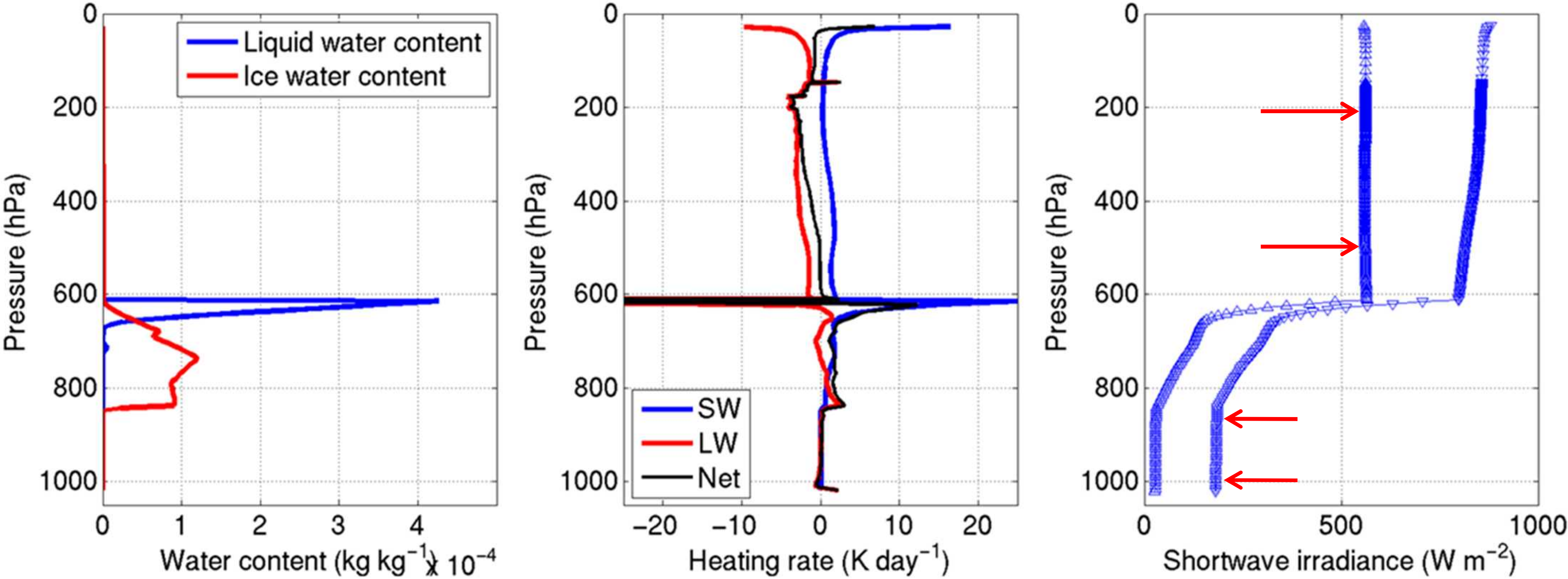
- Use "DARDAR" CloudSat-CALIPSO cloud mask
- How well is mean cloud fraction modelled?
  - Tend to underestimate mid & low cloud fraction
- How good are models at forecasting cloud at right time? (SEDI skill score)
  - Winter mid to upper troposphere: excellent
  - Tropical mid to upper troposphere: fair
  - Tropical and sub-tropical boundary layer: virtually no skill!
- *Hogan, Stein, Garcon & Delanoe (in prep)*

Ice cloud fraction parameterisation



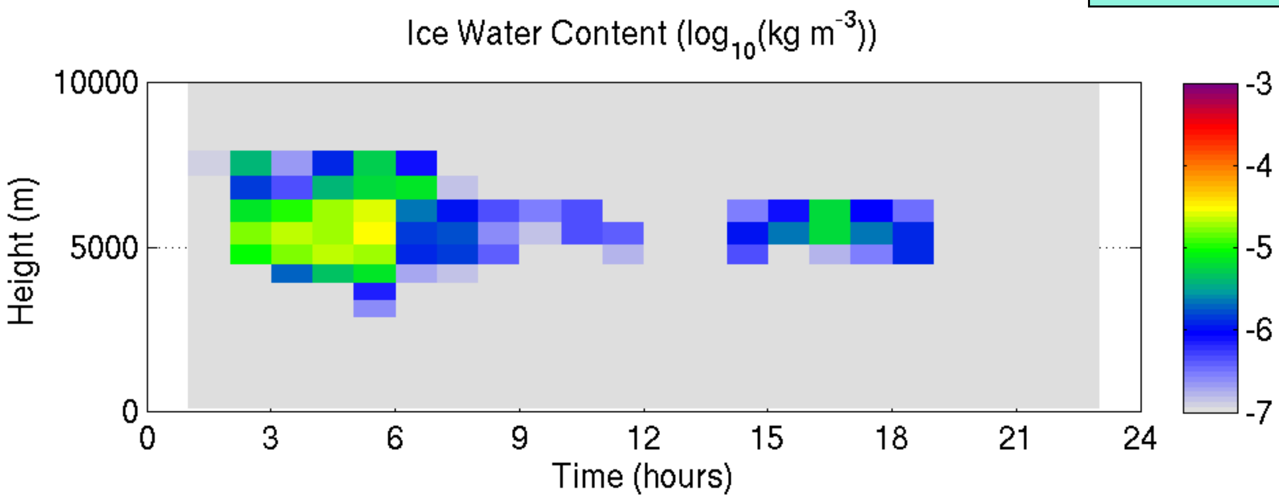
Radiative properties

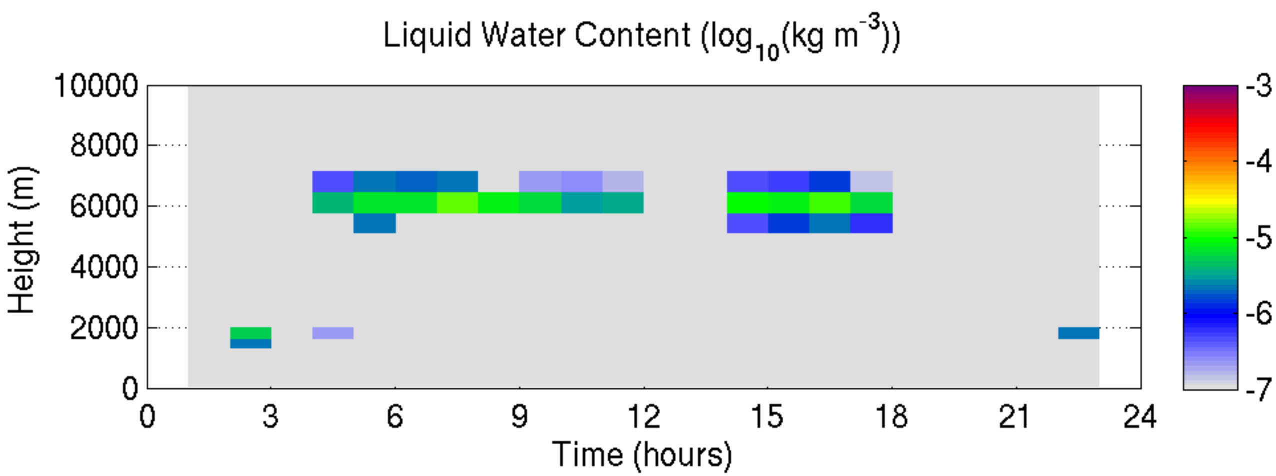
- Using Edwards and Slingo (1996) radiation code
- Water content in different phase can have different radiative impact



Cloudnet processing

- Illingworth, Hogan et al. (BAMS 2007)





- Use radar, lidar and microwave radiometer to estimate ice and liquid water content on model grid