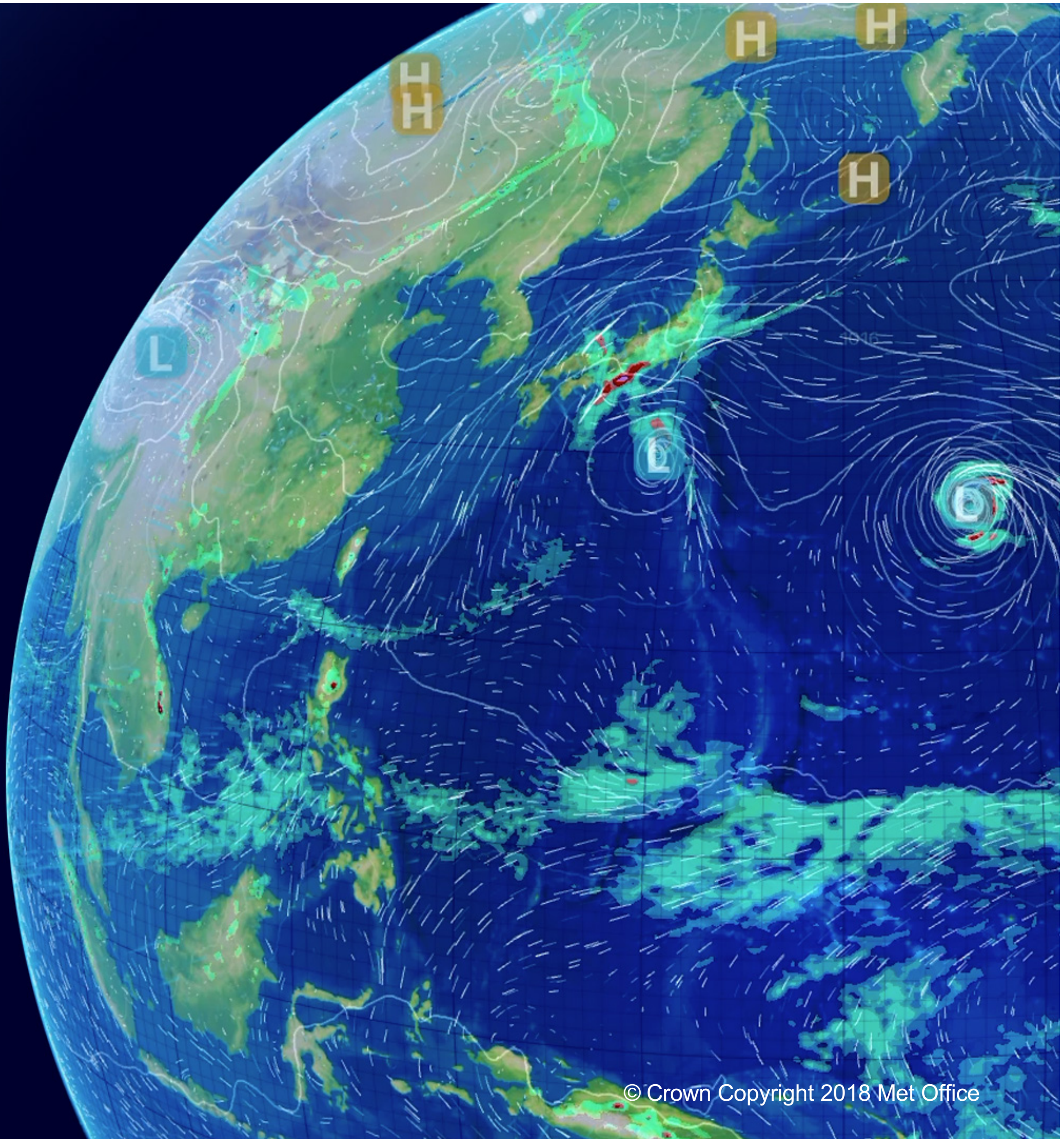
Modelling clouds for weather, climate and beyond...

Ian Boutle

+ many collaborators...



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The real world is complex...

- Computer models used for weather forecasts and climate simulations need to represent all of this complexity.

- BUT, they need to do so in a very efficient manner...

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The forecast problem

$$\frac{D\mathbf{u}}{Dt} = -2\mathbf{\Omega}\times\mathbf{u} - \frac{\nabla p}{\rho} + \mathbf{g} + \mathbf{S}^{\mathbf{u}}$$

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\mathbf{u}) = 0$$

$$\frac{D\theta}{Dt} = S^{\theta}$$

$$p = \rho R T$$

- Core of the model solves the Navier-Stokes equations
- Must discretise these onto a finite-difference grid to solve

- Weather forecasts take 30-60 minutes (of computer time)
  - Anything shorter, you may as well do things better
  - Anything longer ceases to be a forecast
- Current global forecast model runs on 4752 processors
  - New supercomputer (Cray XC40) installed in 2016
- So to fit a 7-day forecast into those resources, we can afford 2560 x 1920 x 70 grid points – approx 10km horizontal resolution!

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The parametrization problem

$$\frac{D\mathbf{u}}{Dt} = -2\mathbf{\Omega}\times\mathbf{u} - \frac{\nabla p}{\rho} + \mathbf{g} + \mathbf{S}^{\mathbf{u}}$$

$$\frac{D\theta}{Dt} = S^{\theta}$$

- Many processes exist on a scale <10km, but have an important influence on the weather or climate:
    - Clouds and precipitation
    - Turbulence
    - Radiation
    - Orography (hills and valleys)
    - Surface characteristics (trees, grassland, buildings, ocean)
- The “bulk” effect of these processes, at the grid-scale, needs to be included in the governing equations via source/sink terms
- Parametrizations compute these source/sink terms
- Some processes (e.g. Turbulence) only need parametrizing because of the resolution of the model, whilst others (e.g. Radiation) will always be needed

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Contents

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1. Very high-resolution modelling for aviation at Heathrow airport

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Heathrow and fog

- Heathrow is one of the busiest airports in the world – runs at ~99% capacity
- When visibility is low, space between aircraft must be increased -> lower capacity -> cancelled flights
- 75% of delays are weather related, half of this is due to low visibility
- Very expensive + lots of grumpy passengers
- With accurate forecasts, can plan ahead to mitigate the effects
- How can we improve our forecast accuracy?

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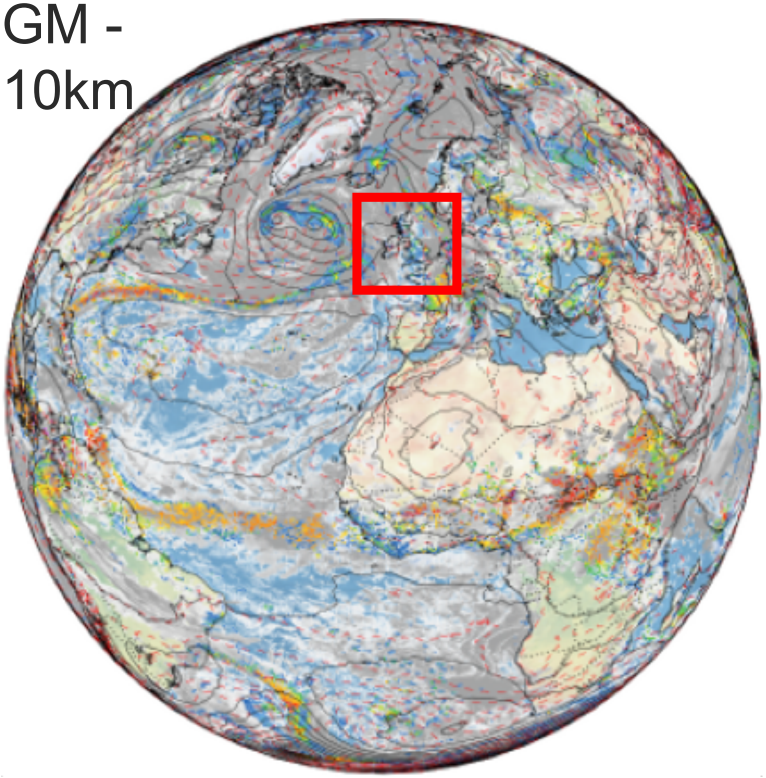
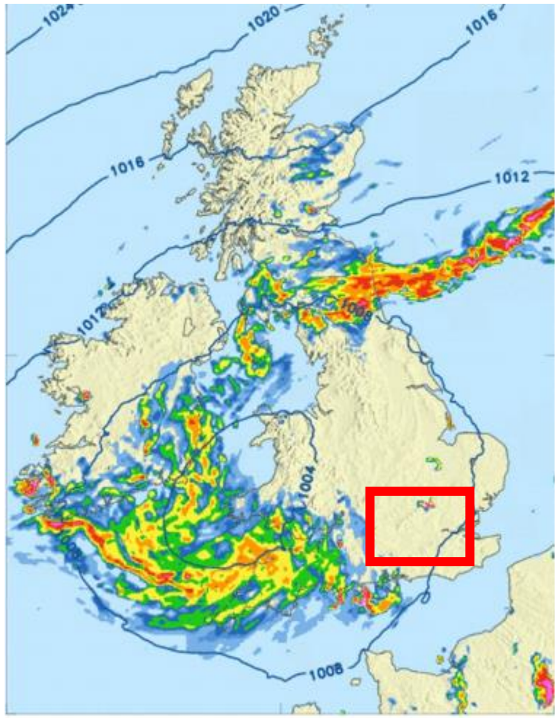
Model hierarchy

GM - 10km



UKV – 1.5km



- Don't just run 10km global model
- Region of interest is UK, so nest a 1.5km model inside this
- HUGE benefit in detail and accuracy
- What if we added another level?

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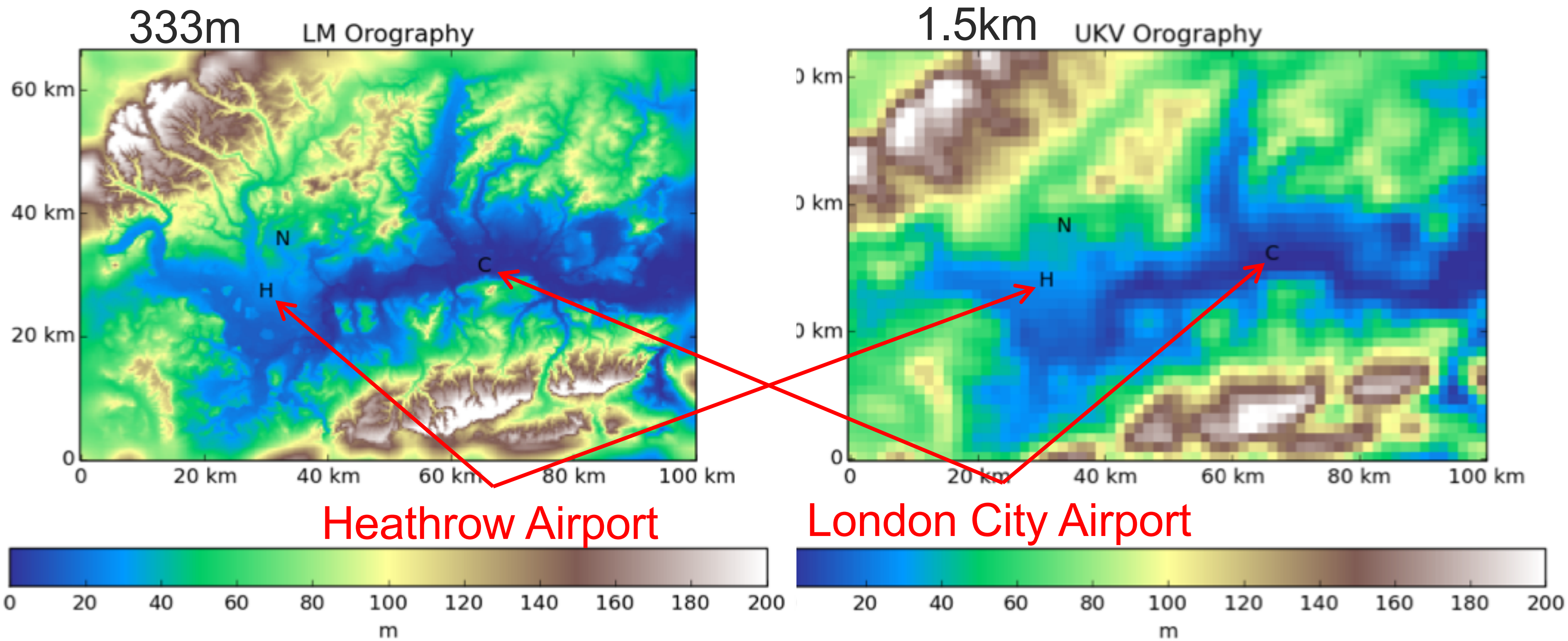
The London Model

- Enhanced detail in terrain features, land-surface characteristics
- Better resolution of atmosphere
- Less reliance on parametrizations



Boutle et al. (2016, QJRMS)

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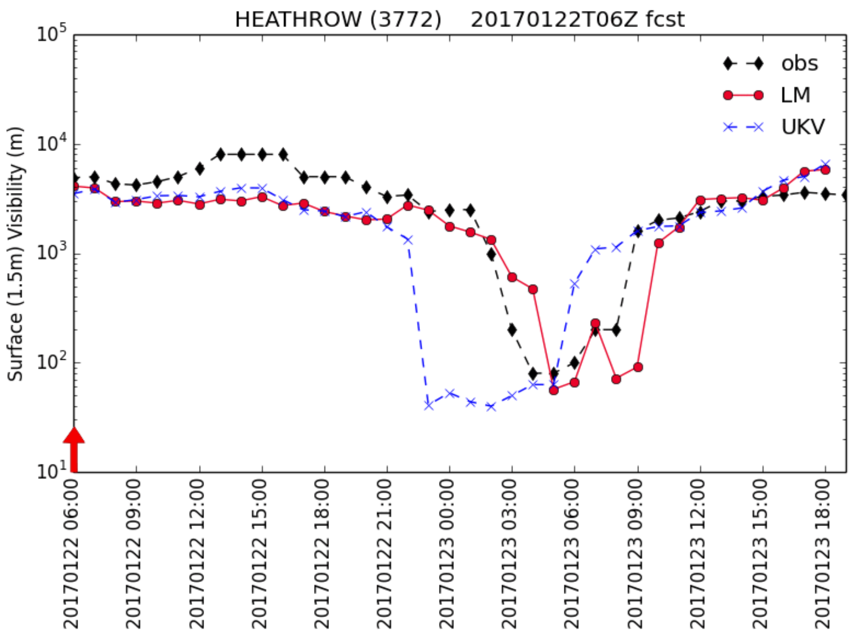
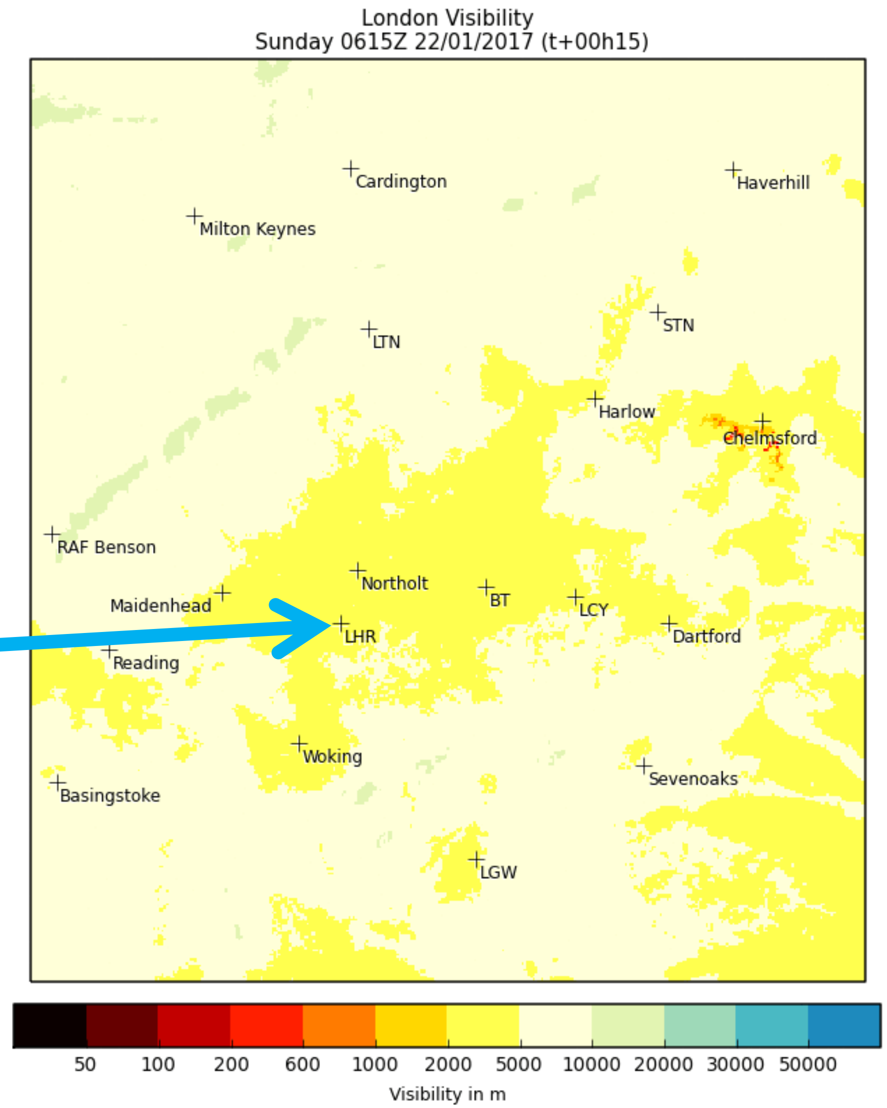
An example from last winter:





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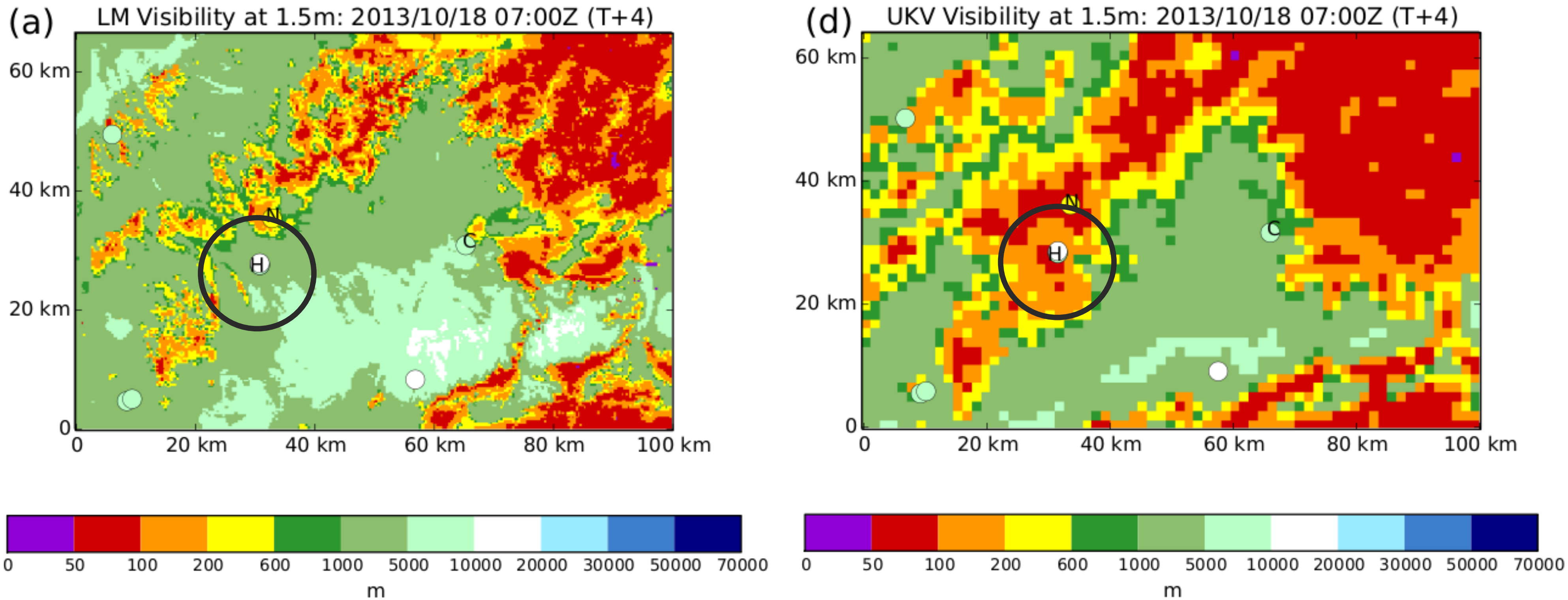
Not just an HD picture

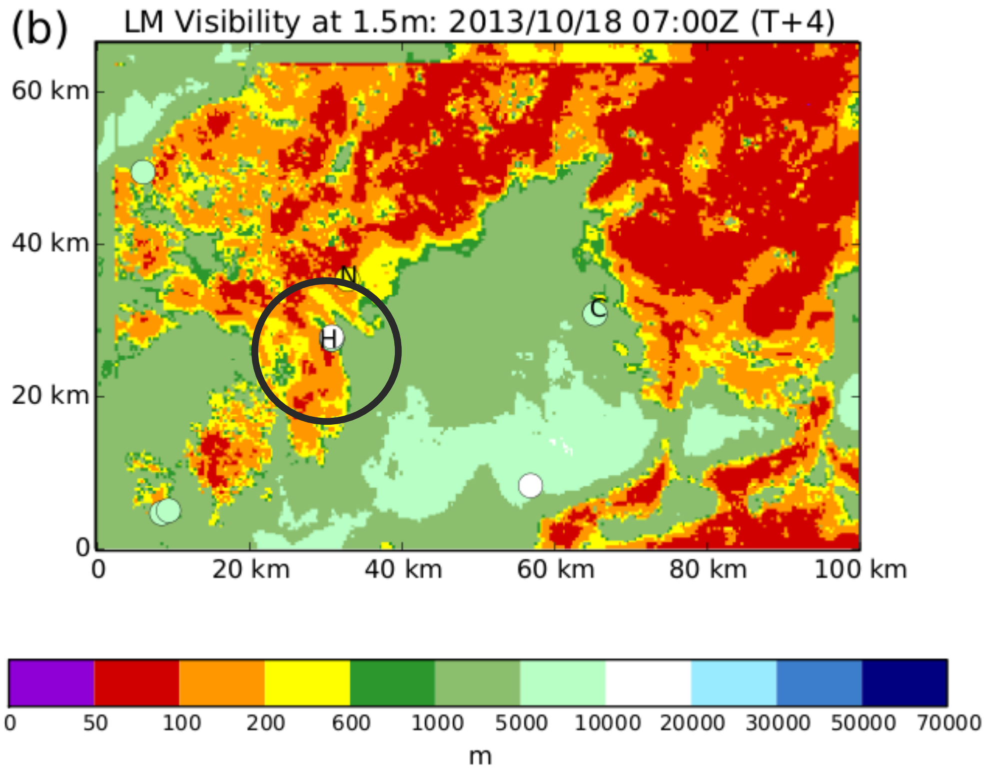
- The enhanced resolution genuinely alters the evolution of the fog
- Why?

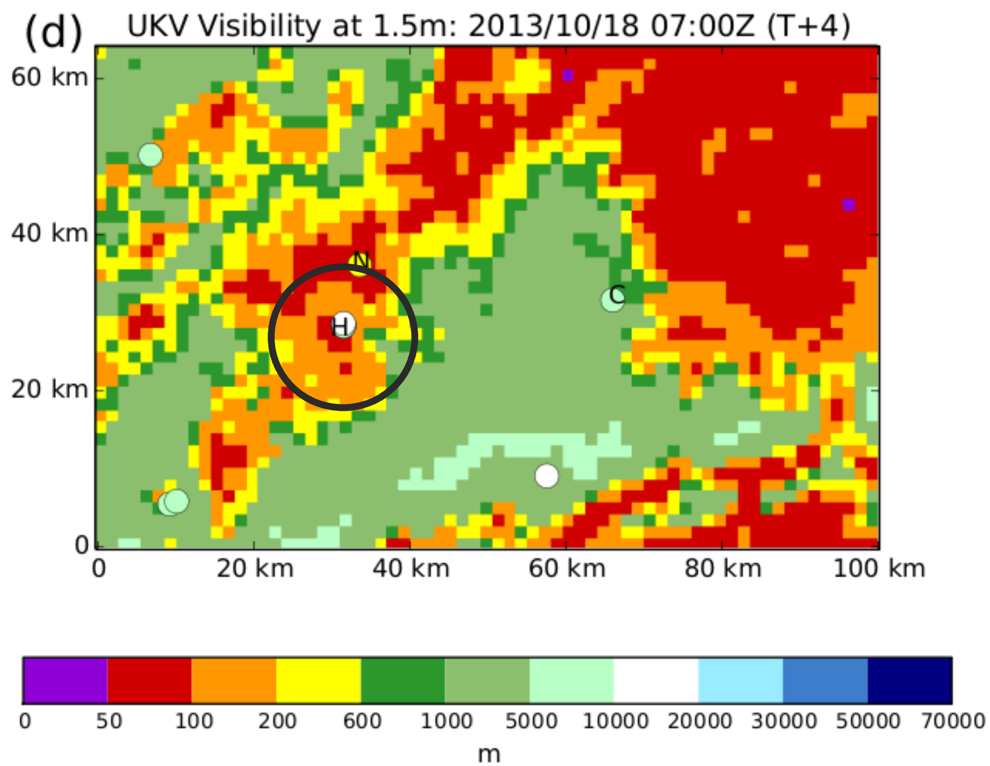


Boutle et al. (2016, QJRMS)

Smoothed terrain

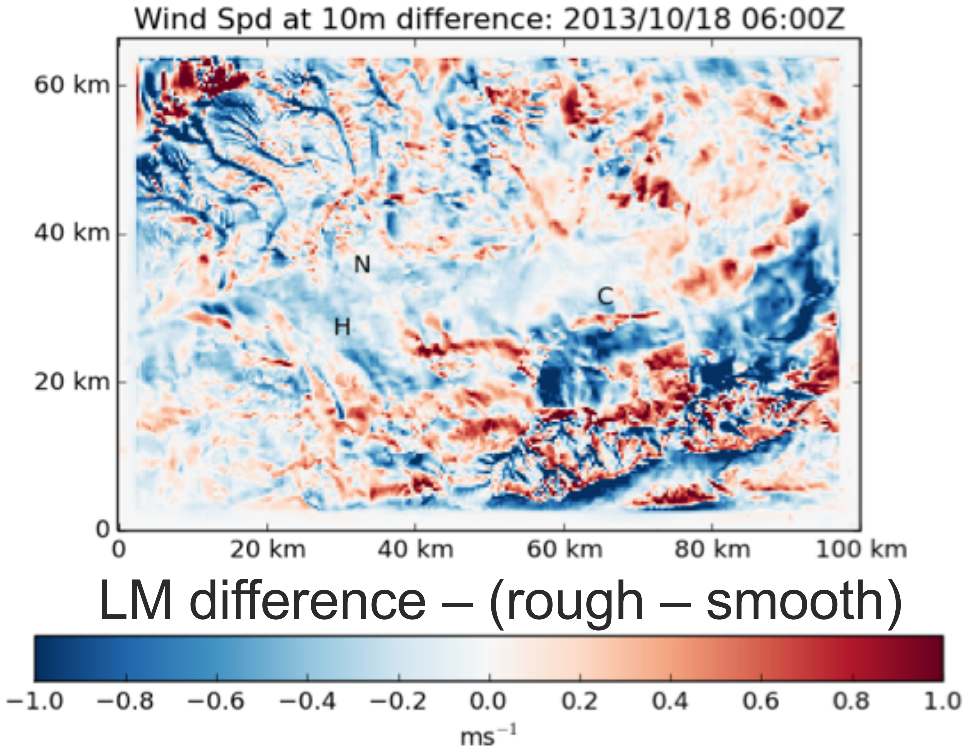
- Use the lower resolution orography field from the UKV in the LM, gives big change in fog evolution





Boutle et al. (2016, QJRMS)

A turbulence feedback



LM difference – (rough – smooth)

- Rougher terrain strongly affects the near surface wind field
- This extra variability in the wind-shear affects the structure of the atmosphere:
  - More turbulent
  - Extra turbulence mixes warmer air down from aloft
  - Warmer air prevents fog formation
- A genuine benefit of higher resolution, but could we parametrize it at lower resolution?

Boutle et al. (2016, QJRMS)

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2. Cloud parametrization improvements for the latest climate model

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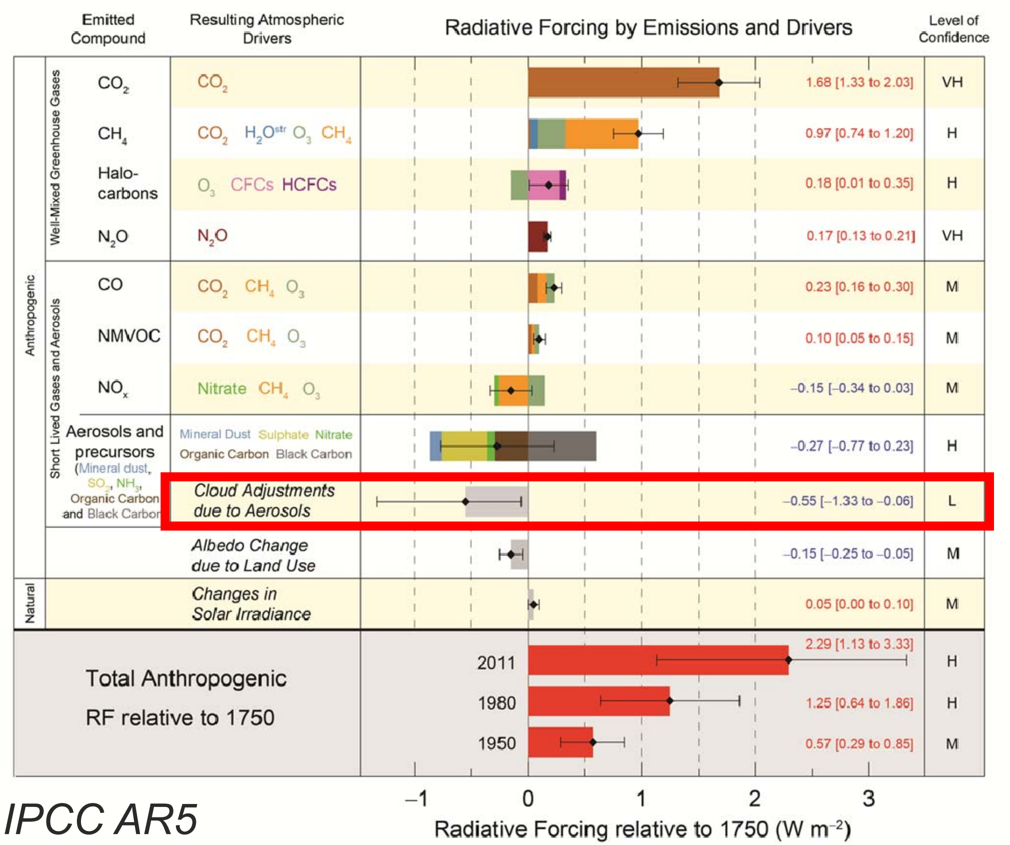
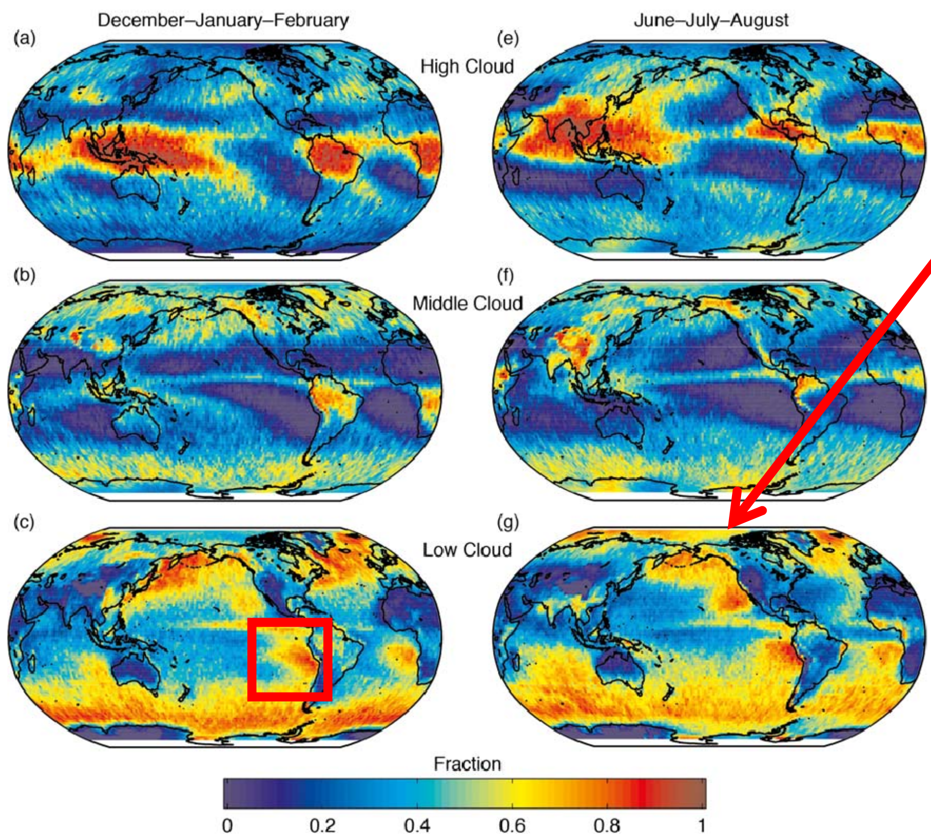
Clouds and climate



IPCC AR5

- Clouds represent the single biggest uncertainty in climate models
- How they respond to a warming climate could EITHER significantly reduce the amount of warming OR significantly increase it!
- Hence a strong requirement to improve their modelling

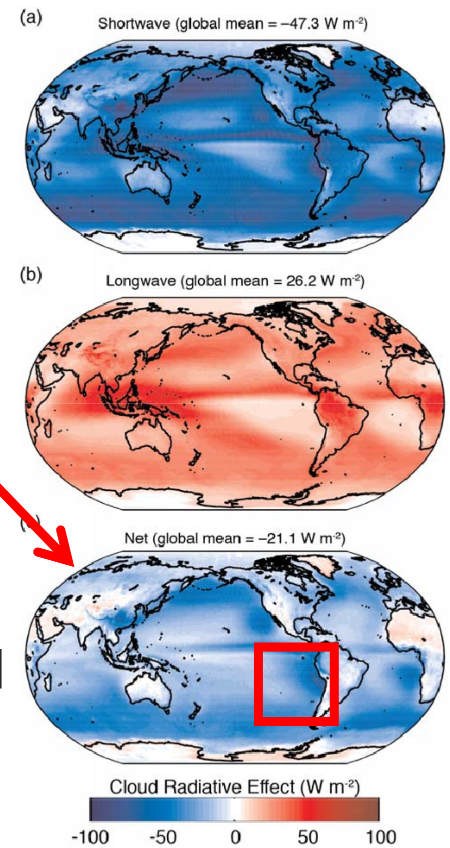
Existence and effect in the climate system



Low clouds are the most prevalent cloud type on the planet

They provide a cooling to the climate system

Whether there are more (wetter) or less (warmer) of them could create a negative or positive feedback



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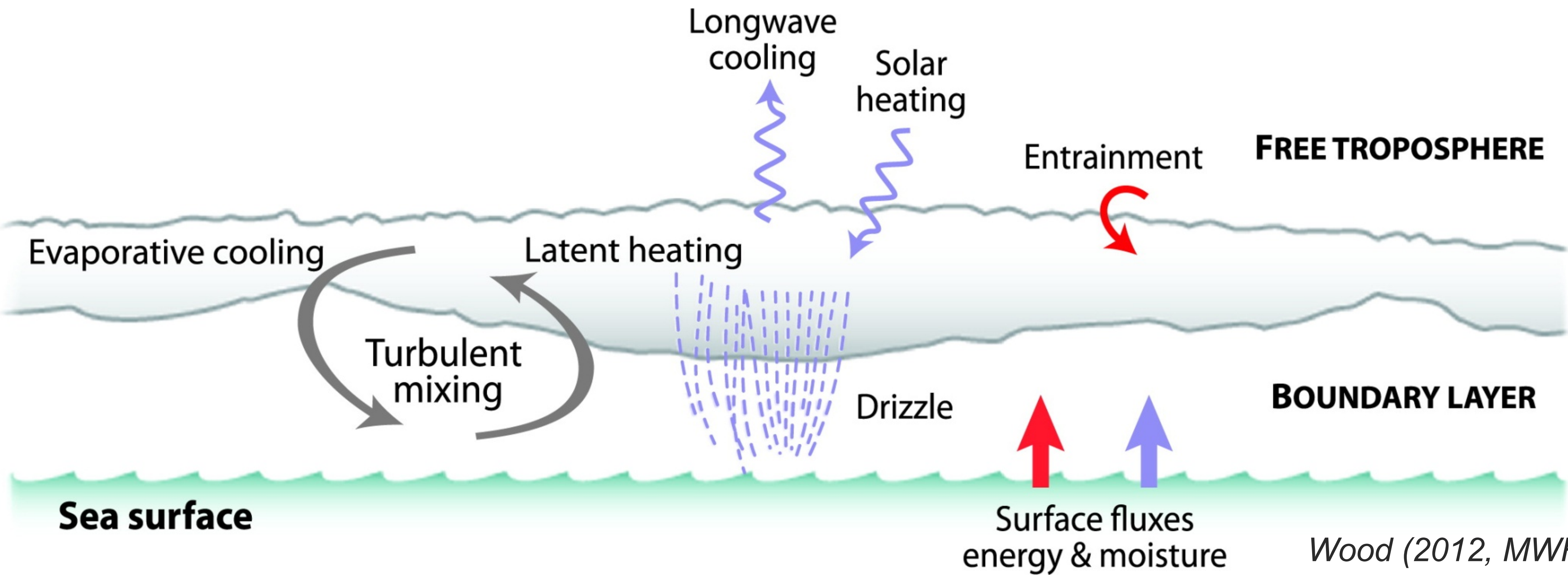
Why is modelling low clouds so difficult?

- Combination of many different physical processes
- Most of which are parametrized
- Fundamental physics of many is poorly understood



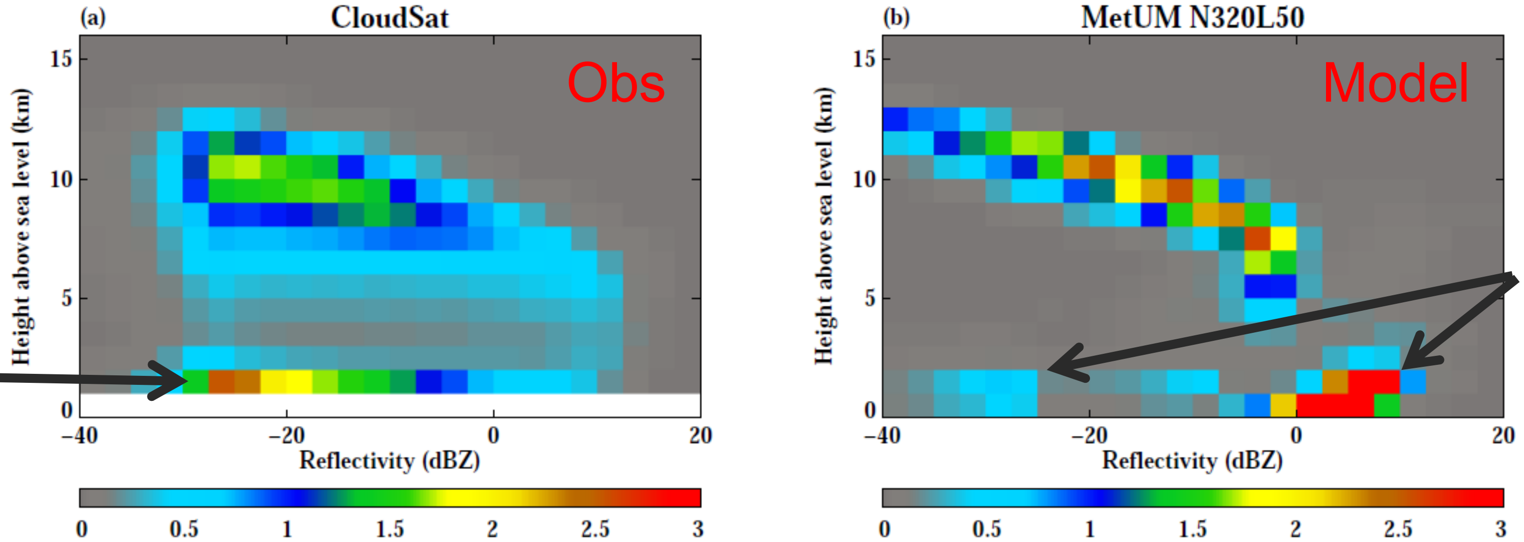
Wood (2012, MWR)

“Dreary” state of precipitation in climate models

- CloudSat sees the cloud and precipitation falling below it
- Higher reflectivity -> bigger drops

Californian Stratocumulus - DJF 2006

Continuous transition from cloud to rain



Two distinct modes – one for cloud, one for rain

- Not unique to our model!

Bodas-Salcedo et al, (2008, JGR)

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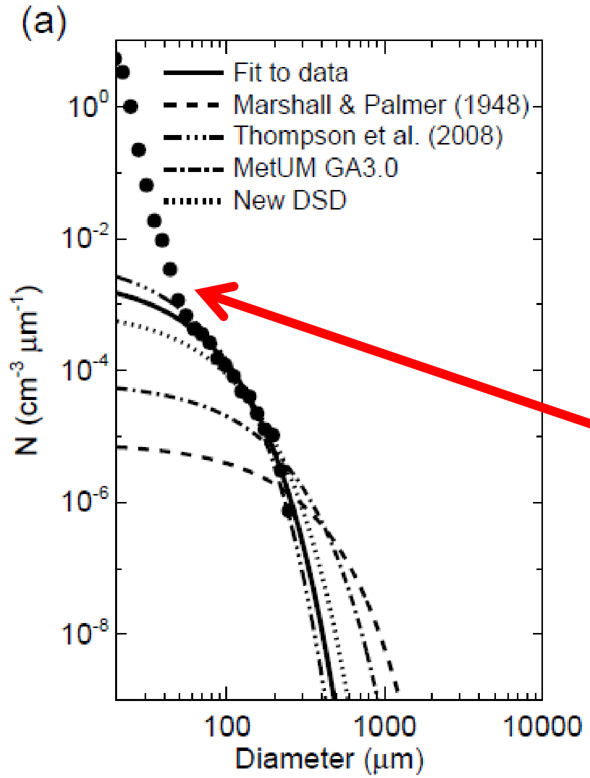
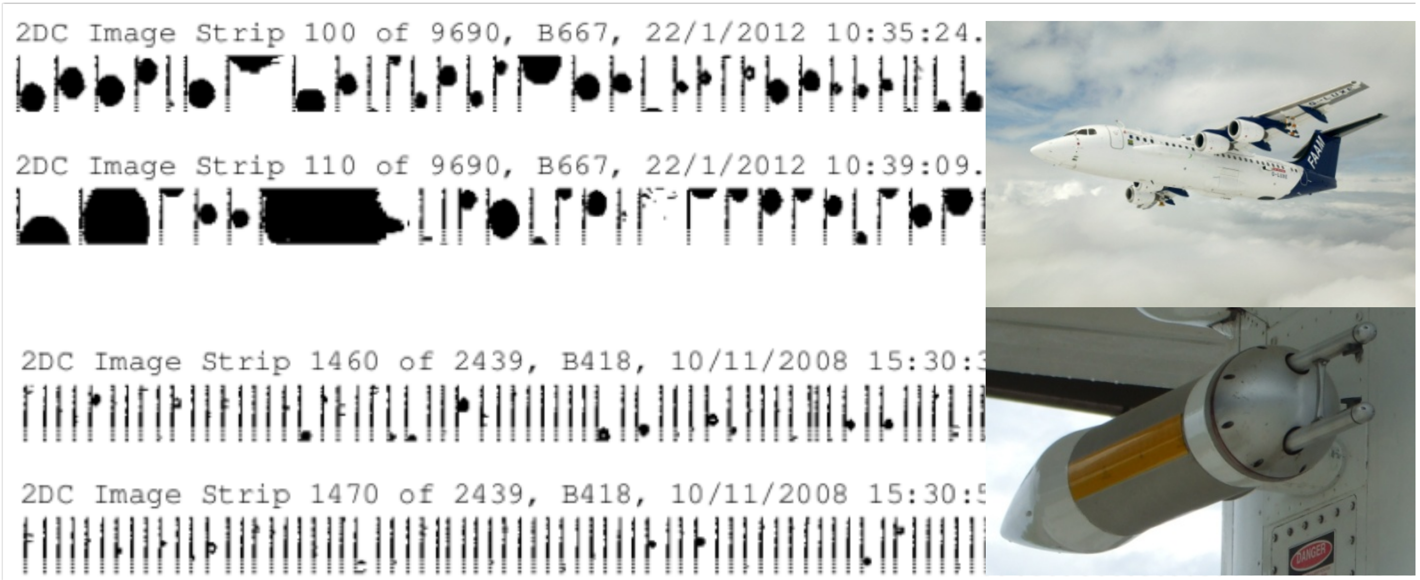
Microphysical modelling





- Equations for droplet growth are well known and understood – easy to solve
- Each grid-box contains a spectrum of particles of different sizes
- Could model each different sized particle explicitly – bin scheme (too expensive ~30+ prognostic variables)

Abel & Boutle (2012, QJRMS)

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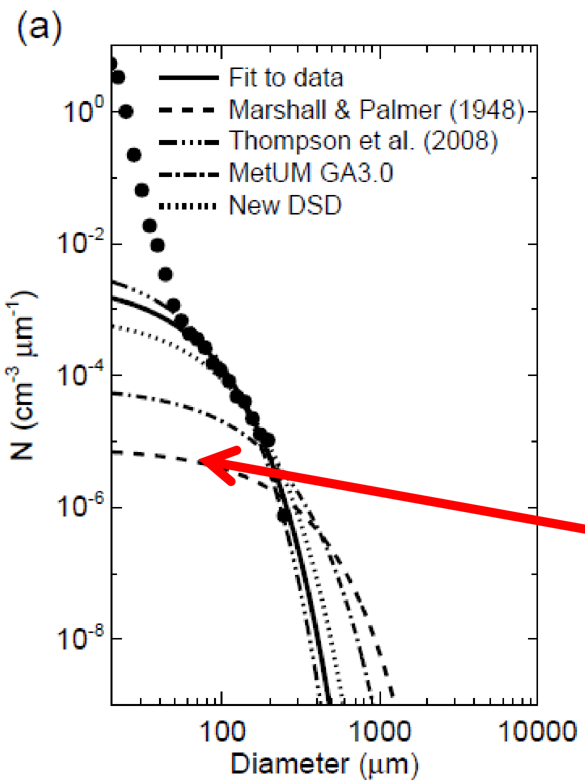
Rain drop size distribution



- Hence have to assume a size distribution of particles and integrate over it – bulk scheme (2 prognostic variables, cloud water & rain water)
- Assume the number of rain-drops (*N*) is related to their diameter (*D*) by:

$$N(D) = N_0 \exp(-\lambda D)$$

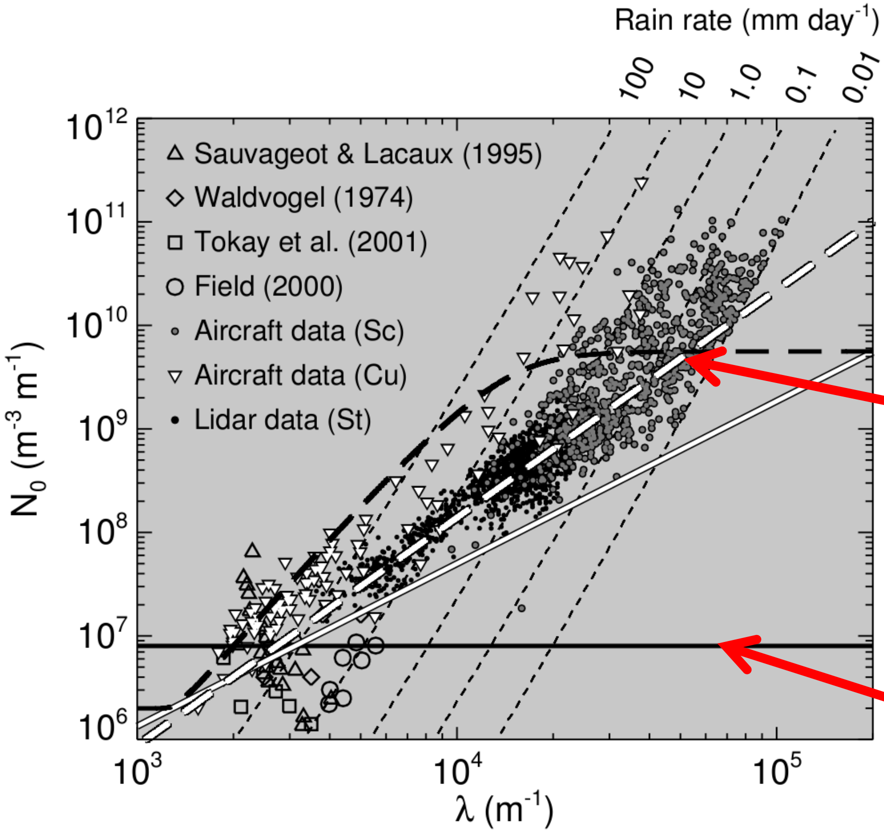
- Most models use Marshall & Palmer (1948):

$$N_0 = 8 \times 10^6$$

- Doesn't appear to match reality very well…

Abel & Boutle (2012, QJRMS)

Relationship between N_0 and rain-rate



- Many in-situ aircraft observations + surface radar/lidar/distrometer observations
- Suggests a relationship between N_0 and λ:

$$N_0 = 0.22\lambda^{2.2}$$

- λ is a physical quantity, related to the total mass of rain

$$N_0 = 8\times 10^6$$

Abel & Boutle (2012, QJRMS)

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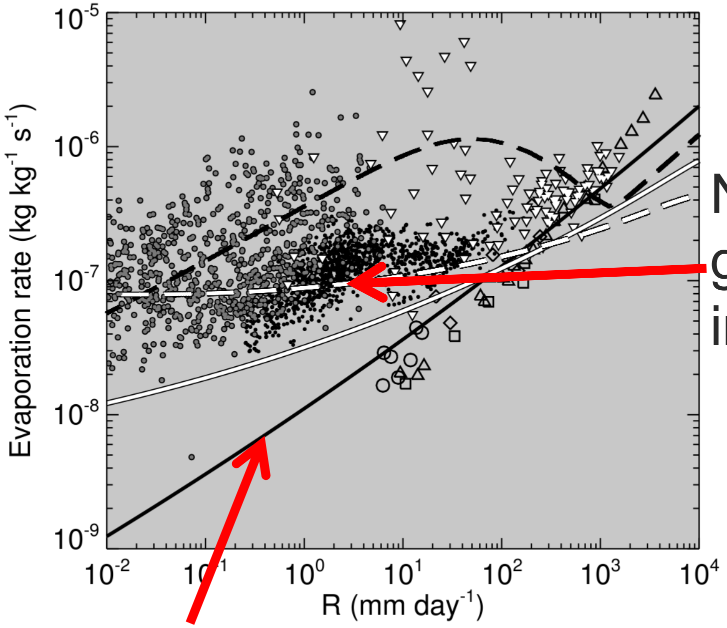
How precipitation physics depends on this

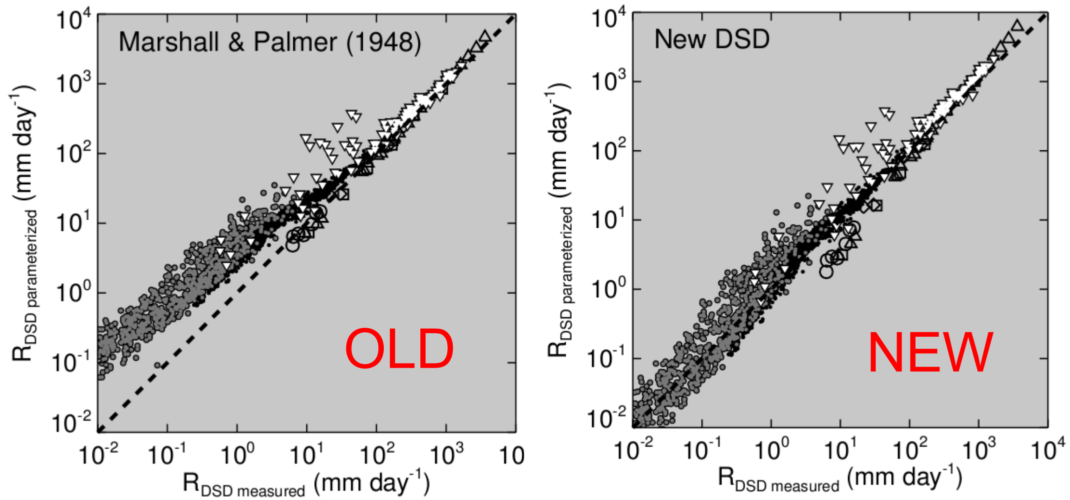
- Evaporation of rain-drops



New-method greatly improves this

Old-method under-estimated the evaporation rate

- Fall-speed of rain-drops



Old-method over-estimated the fall-speed

New-method greatly improves this

Abel & Boutle (2012, QJRMS)

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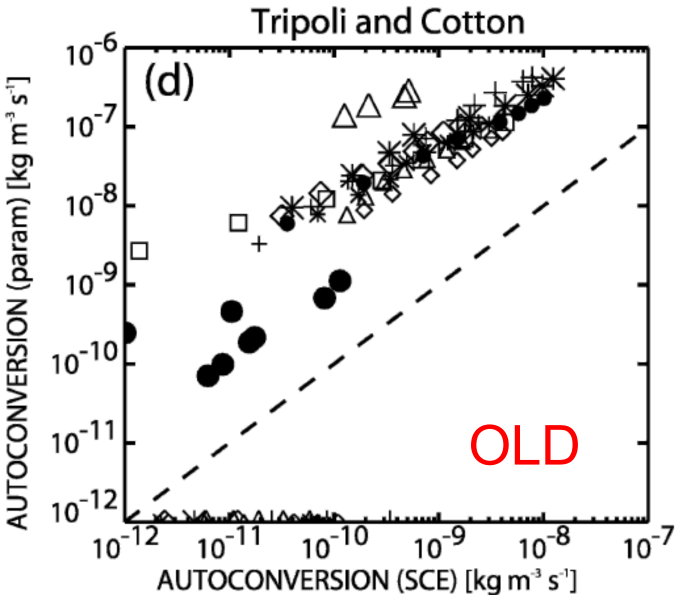
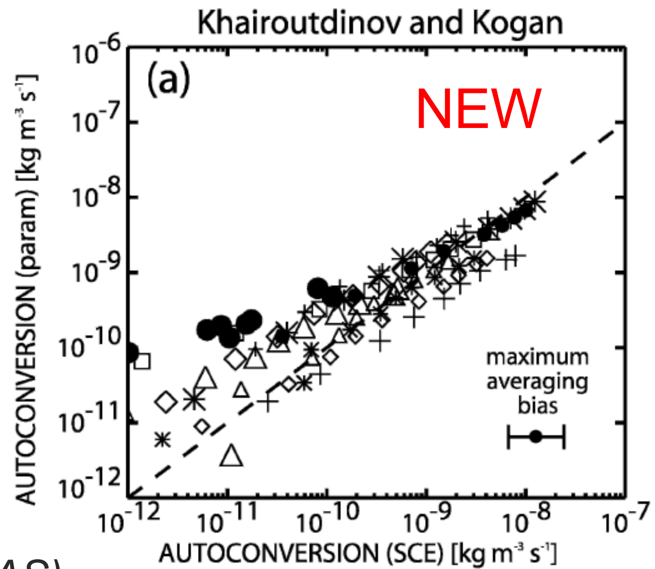
Rain creation processes

- Conversion of cloud to rain treated by a simple power-law:

$$\frac{\partial(qrain)}{\partial t} = C(qcl)^{A}(N_d)^{B}$$

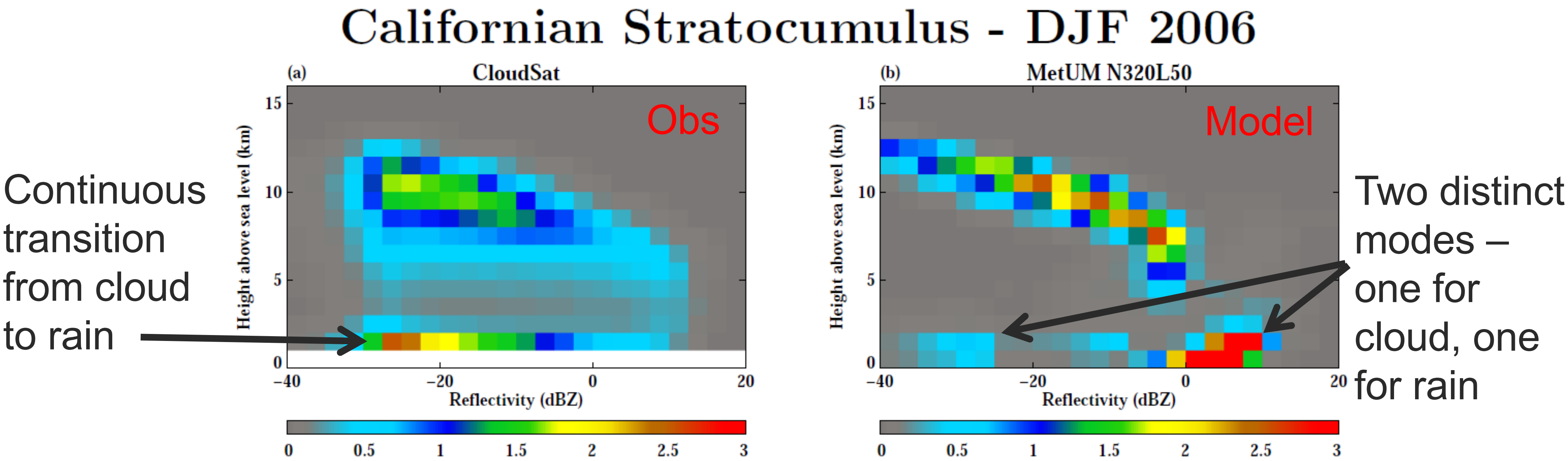
- qx=mass of cloud/rain, Nd=number of cloud droplets
- A, B & C are empirically determined constants
- Old scheme (TC) over estimated rain-creation compared to observations – replace with new scheme (KK)





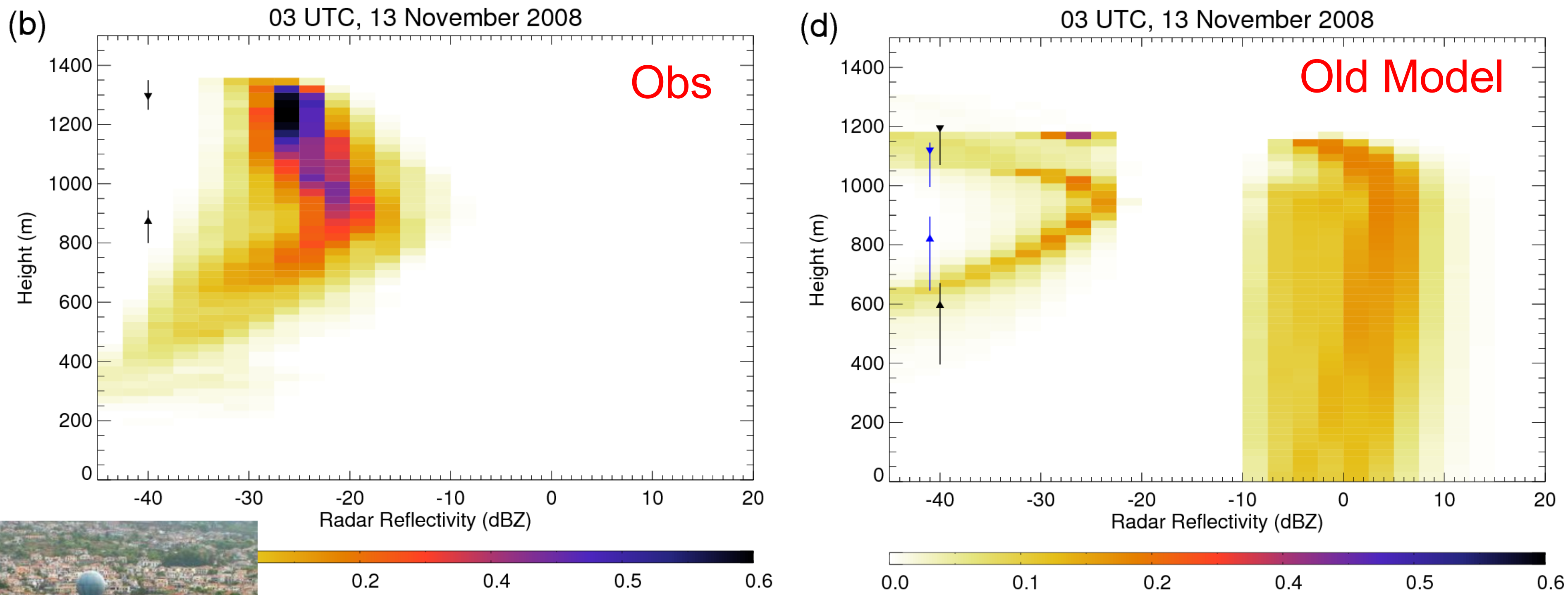
Wood (2005, JAS)

Do we understand this?



- Model over-estimates rain creation, over-estimates rain fall-speed, under-estimates rain evaporation...
- Un-surprising that there is excessive rain and two distinct modes.

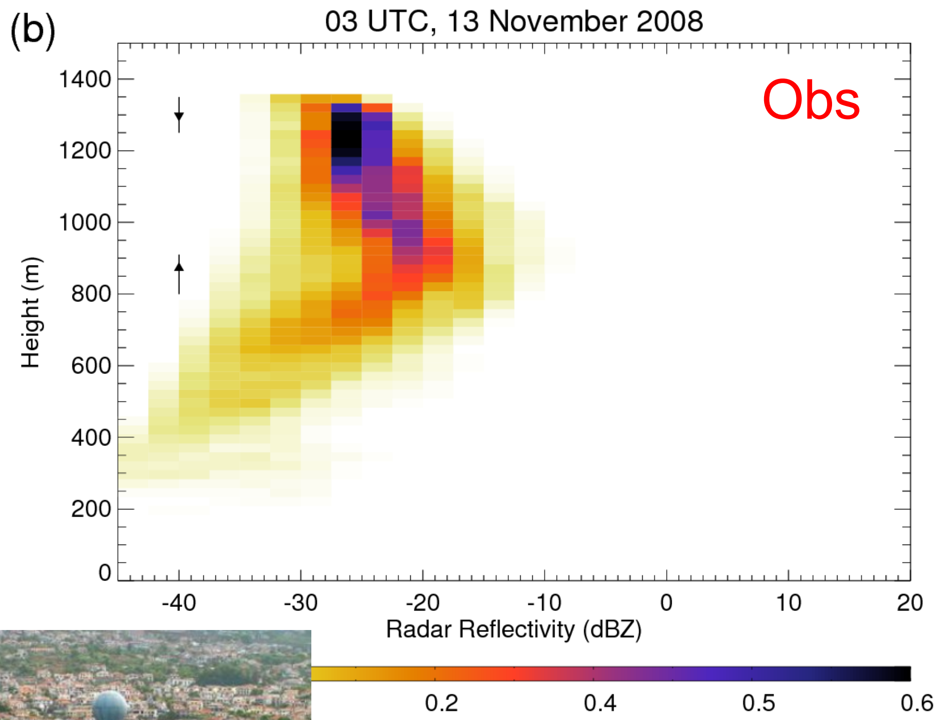
Zoom in on the low cloud

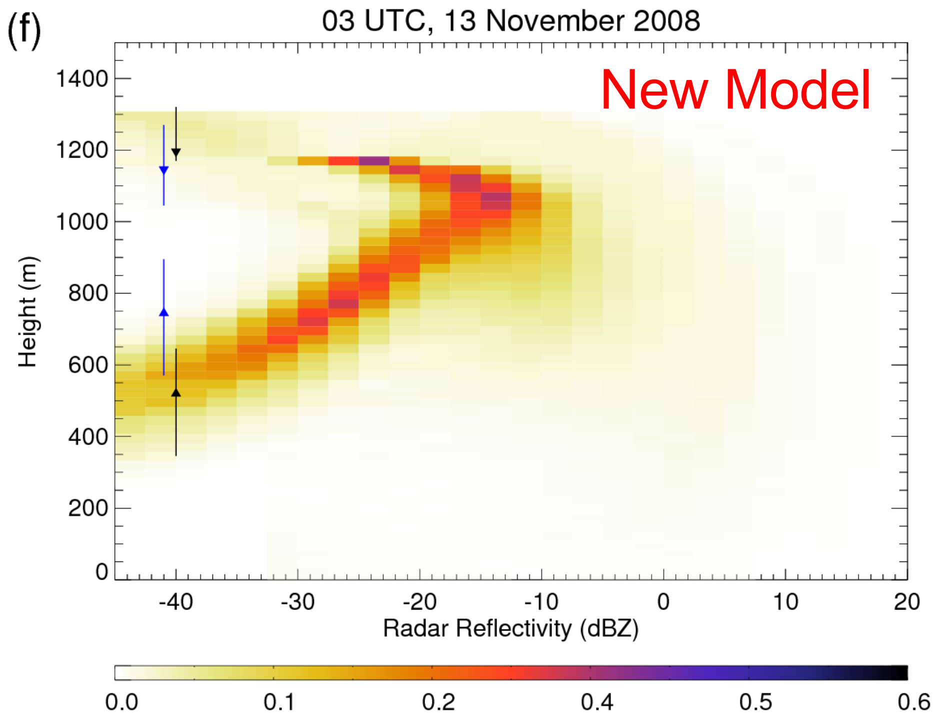


Boutle & Abel (2012, ACP)

Zoom in on the low cloud

- Slower rain-creation lowers the peak reflectivity produced as rain is forming





- Slower fall-speed and more evaporation stops fast falling to the surface and gives reduction in reflectivity below cloud

Boutle & Abel (2012, ACP)

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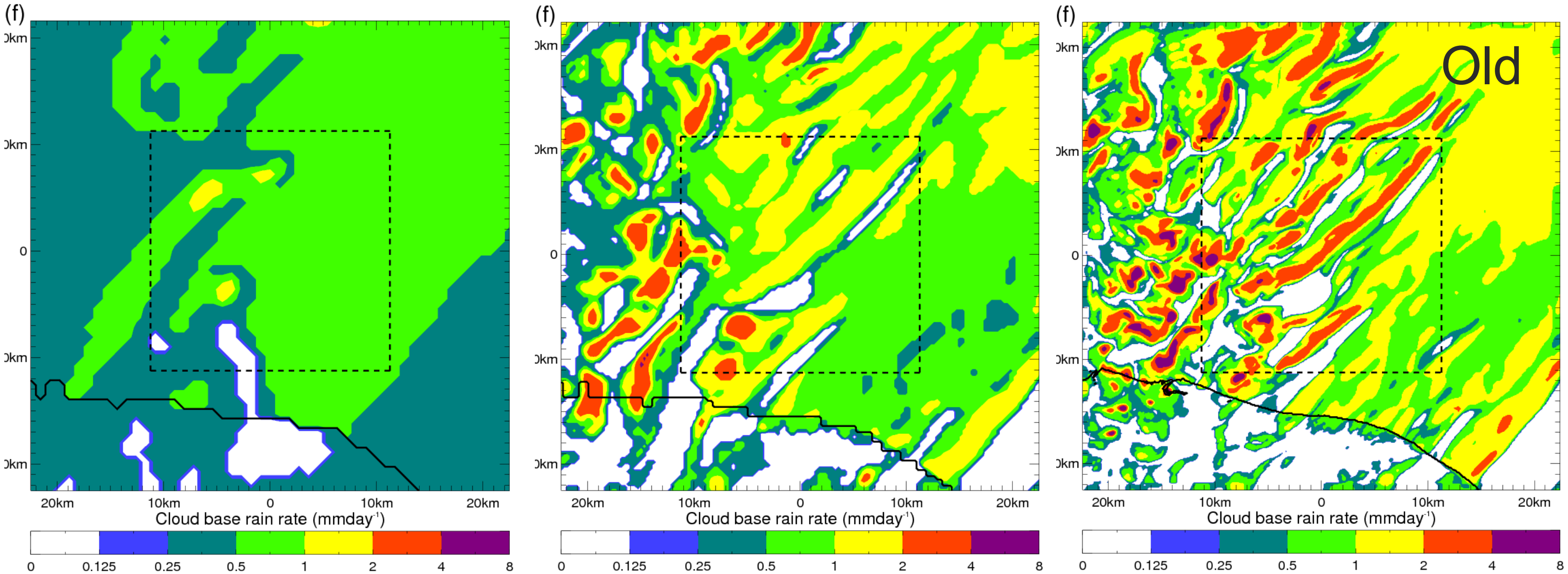
But... There's a problem



Low resolution – climate model

Intermediate

High resolution

- Old climate model actually gave the correct mean surface rain-rate
- Cloud processes are highly nonlinear, so increasing model resolution increases the surface rain-rate (to excessive amounts)

Boutle et al. (2014, MWR)

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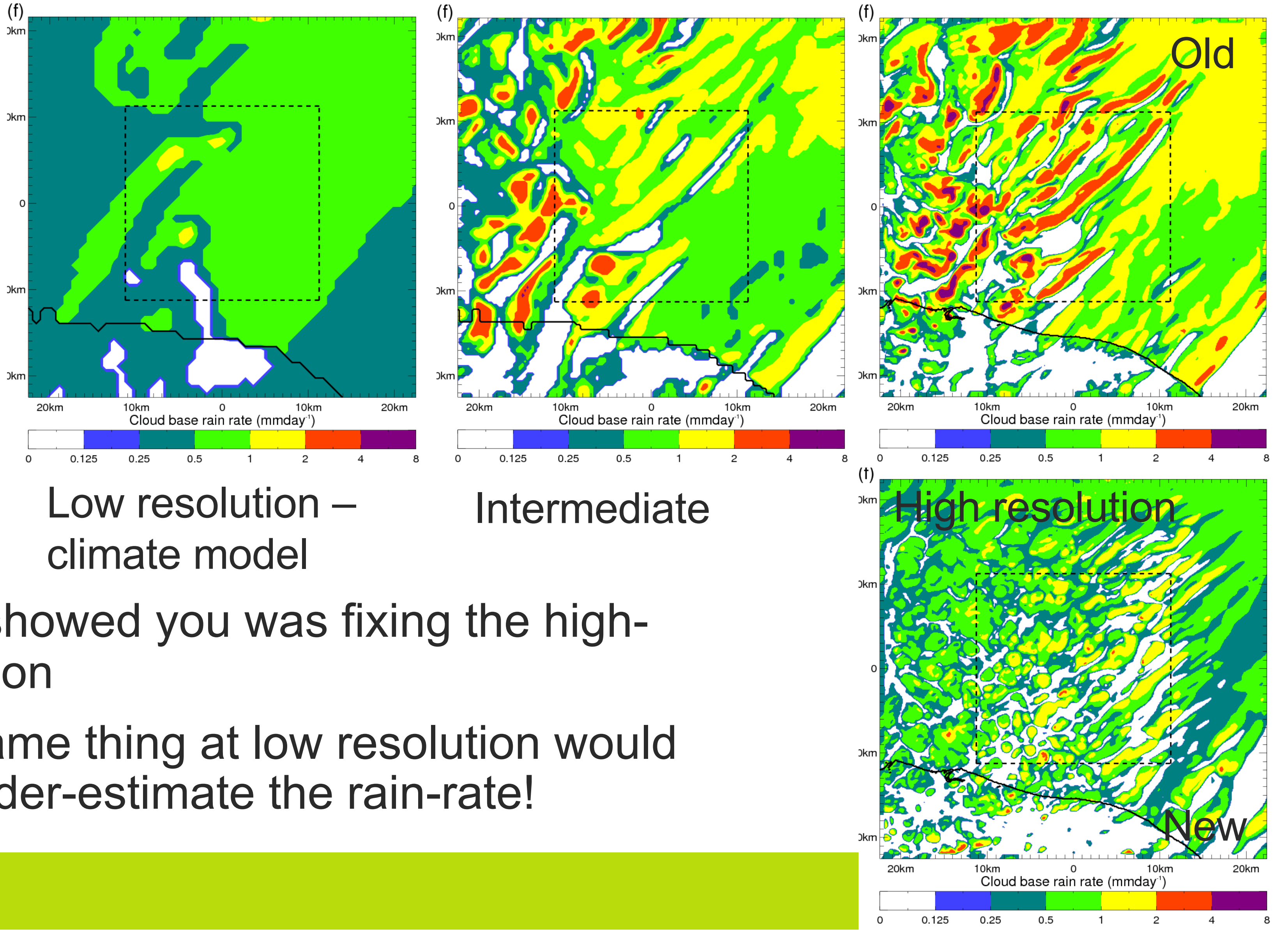
But... There's a problem



- What I've just showed you was fixing the high-resolution version
- Applying the same thing at low resolution would significantly under-estimate the rain-rate!

Boutle et al. (2014, MWR)

Back to rain creation

- Already showed earlier that rain creation is parametrized as:

$$\frac{\partial(qrain)}{\partial t} = C(qcl)^{A}(N_{d})^{B} \quad \text{OR} \quad M = aq^{b} \quad \text{For simplicity}$$

- In a climate model, we want the grid-box averaged process rate (M), but only have the grid-box averaged *q*
- Hence for b≠1:

$$\overline{M} = \overline{aq^{b}} \neq a\overline{q}^{b}$$

- This introduces a systematic bias into the model

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Analytically correcting the process rates

- Suppose we have some information about the sub-grid distribution of *q*, e.g. that it can be represented by a log-normal distribution:

$$P(q) = \frac{1}{\sqrt{2\pi}\sigma q} \exp\left(-\frac{(\ln q - \mu)^2}{2\sigma^2}\right)$$

- Then we can integrate over the PDF to obtain:

$$\overline{M} = E(f, b) a \bar{q}^b$$

$$f = \frac{\sigma}{\bar{q}}, \qquad E(f, b) = (1 + f^2)^{-b/2} (1 + f^2)^{b^2/2}.$$

- We can improve our estimate of *M* by just knowing *f* and the PDF shape

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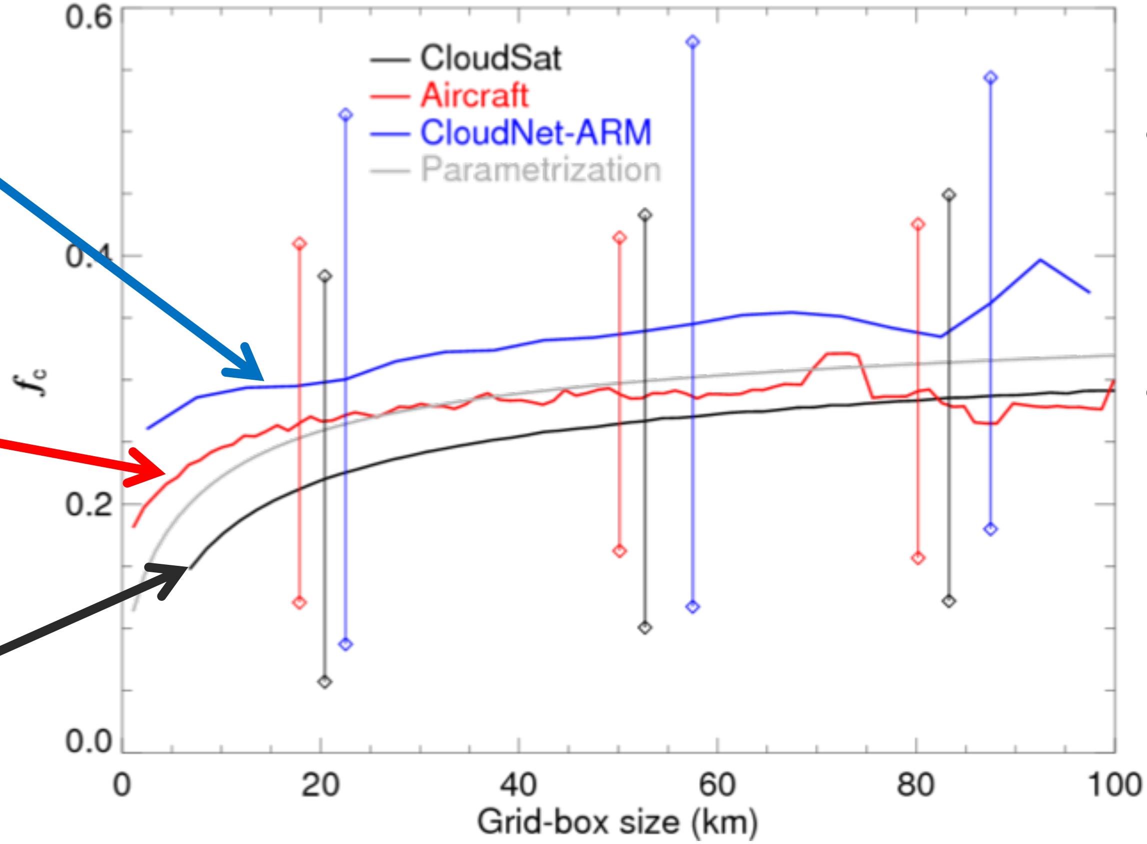
Parameterizing the variability (*f*)



- Variability increases with scale
- Biggest change at smallest scales
- Variability also effected by cloud size (smaller -> more variable)

Boutle et al. (2014, QJRMS)

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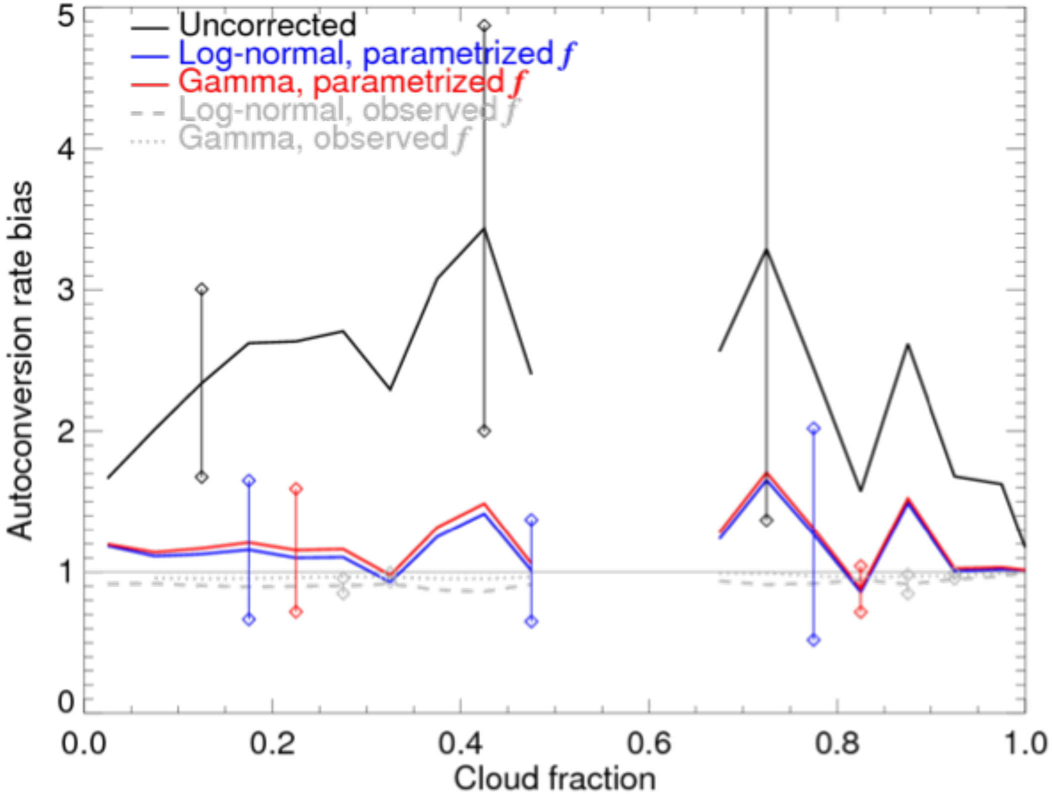
Process rate bias



- At a given scale (here ~50km), compute the exact process rate from high-resolution data, and the process rate based on mean inputs
- Exact rate is under-estimated by a factor of ~4
- Correction is almost exact using PDF method and observed *f*
- And very good using parametrized *f*

Boutle et al. (2014, QJRMS)

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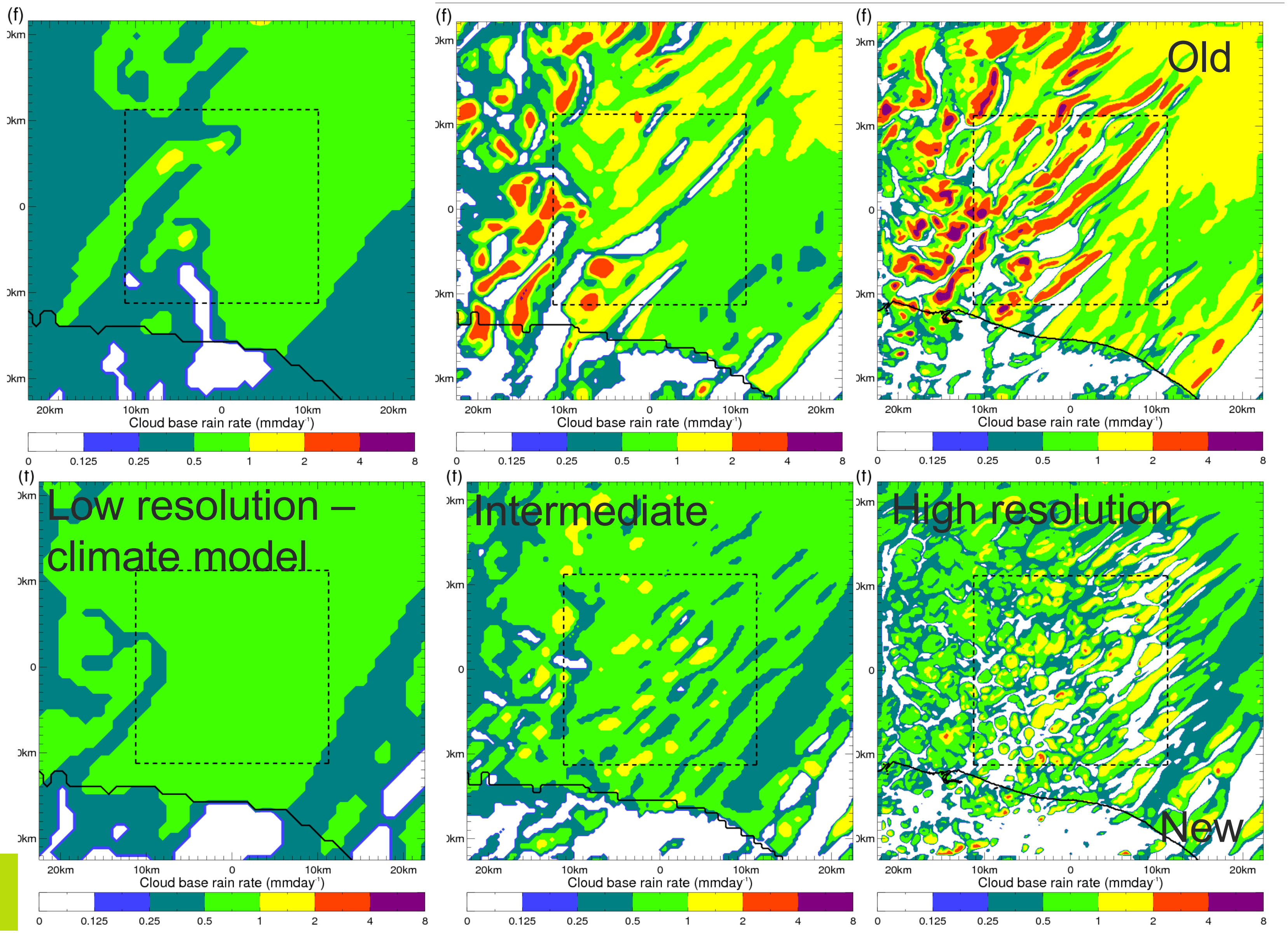
Problem solved!

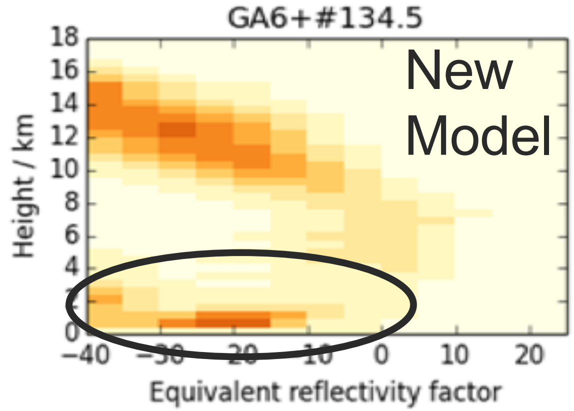
- Now the rain rate is approximately constant, regardless of resolution!

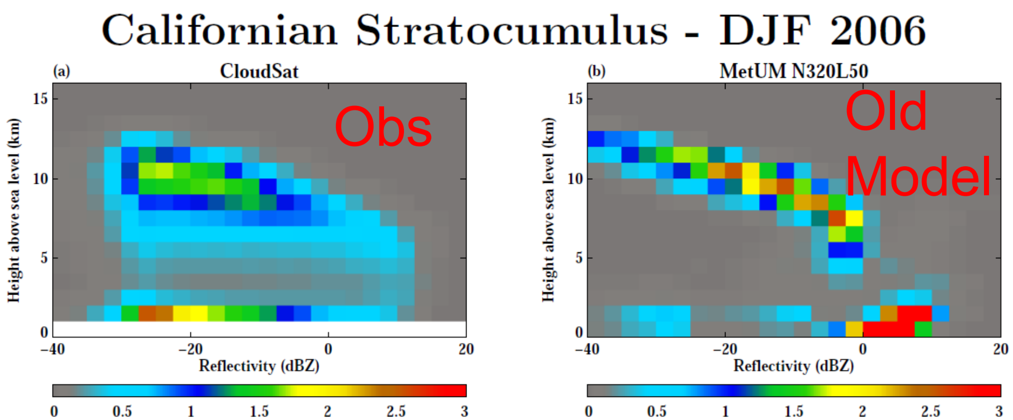
Boutle et al. (2014, MWR)

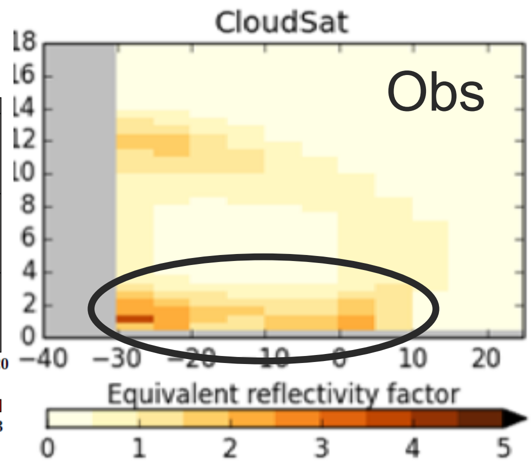


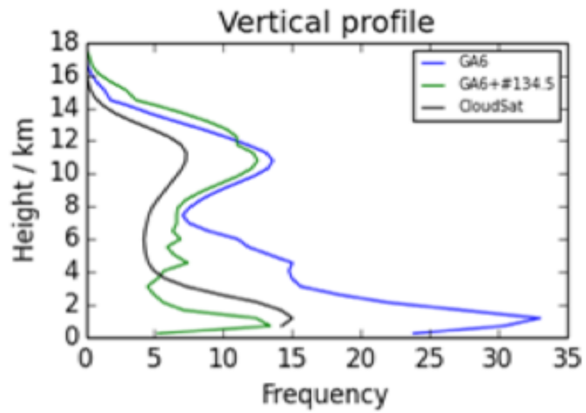
New climate model

- Include these changes in the new climate model
- Transition of cloud to rain is significantly improved
- Greater confidence that model is doing the right thing for the right reason









Walters et al. (2017, GMD)

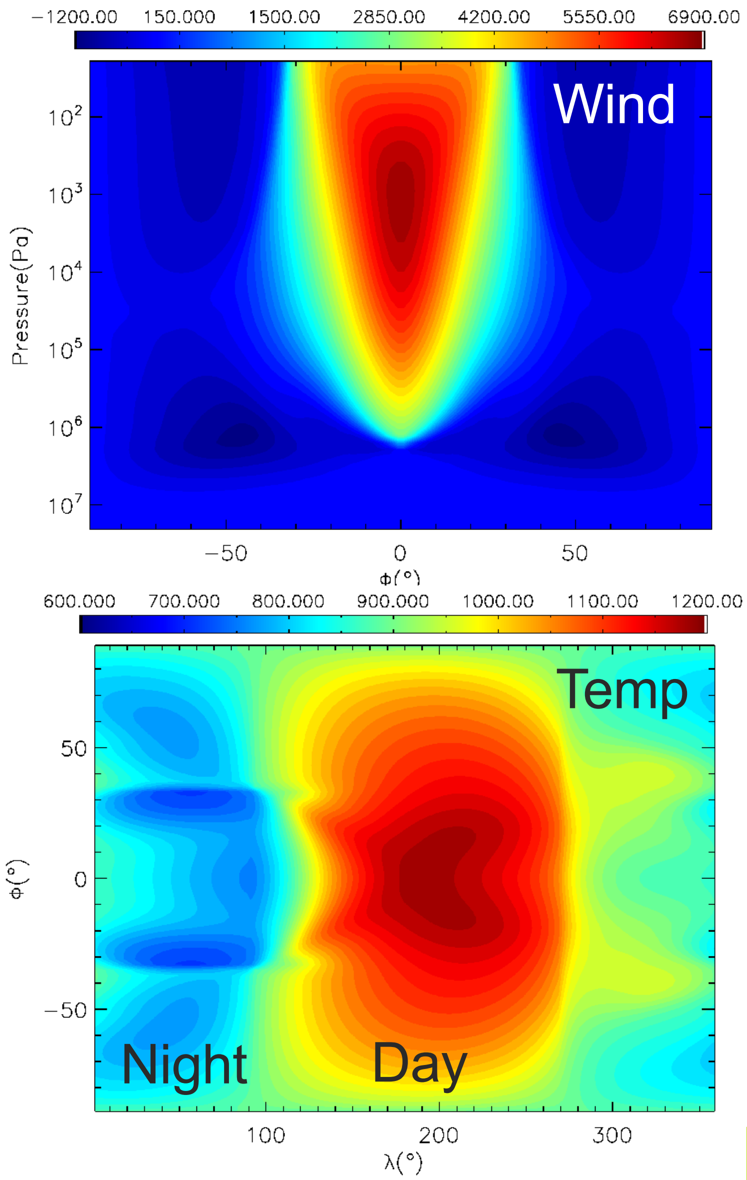
3. Beyond Earth – adapting the model for exoplanet atmospheres

Diversity of the universe

- In the early 1990’s, the first planet orbiting a star other than the sun was found
- Since then, 3584 such planets have been found:
  - 1418 Neptune-like
  - 1205 Gas giant (Jupiter-like)
  - 883 Terrestrial (Earth-like)
  - 53 Super-earth (somewhere between Earth and Neptune)
- Modelling provides a method of interpreting the (limited) observations, understanding the planetary universe, and hunting for life...

Hot Jupiters

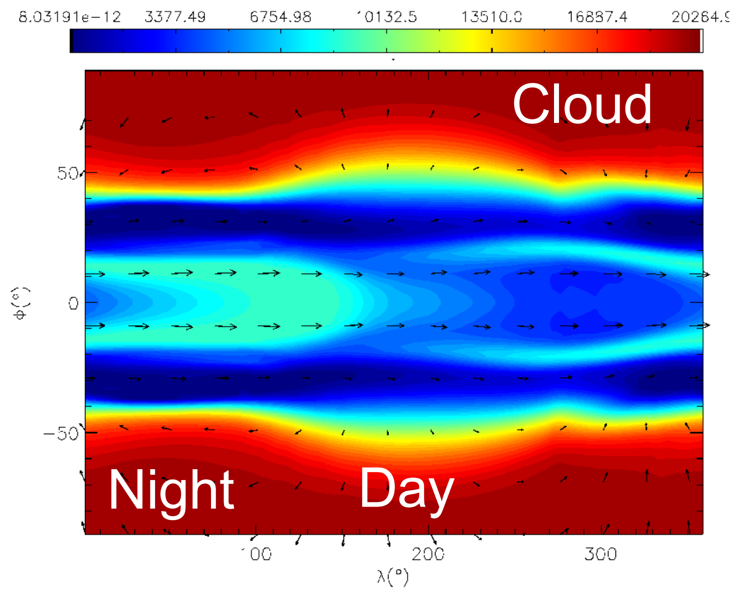
- Best observed – large gas giants orbiting very close to parent star – tidally locked – same side always facing the star
- Some observations of temperature (~1000 K) and wind-speed (~5000 m/s)
- Change the stellar-spectra and planetary parameters (orbit, mass, radius, ...) and the model can produce a credible simulation of this environment!
- Raises all sorts of further questions about structure of the atmosphere - at this temperature metal species (e.g. TiO_2) will condense

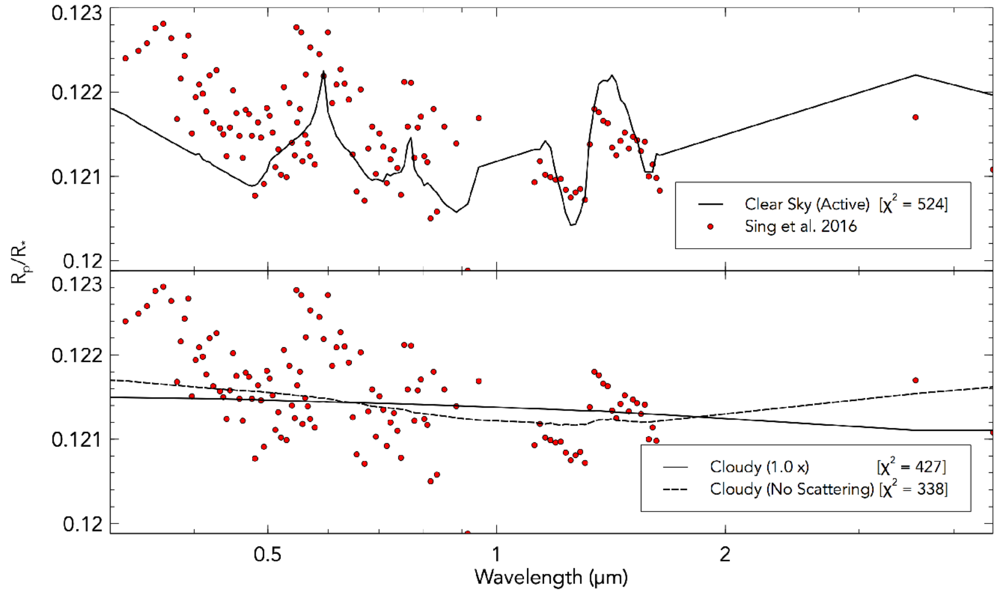


Lines et al. (2018, A&A)

Cloudy exoplanets

- Couple model to metallic cloud formation code developed at St Andrews University
- Produce simulated observations from model and compare to actual observations
- Cloudy model is better fit than clear sky, but differences suggest the physics is still incomplete
- Role of chemistry?

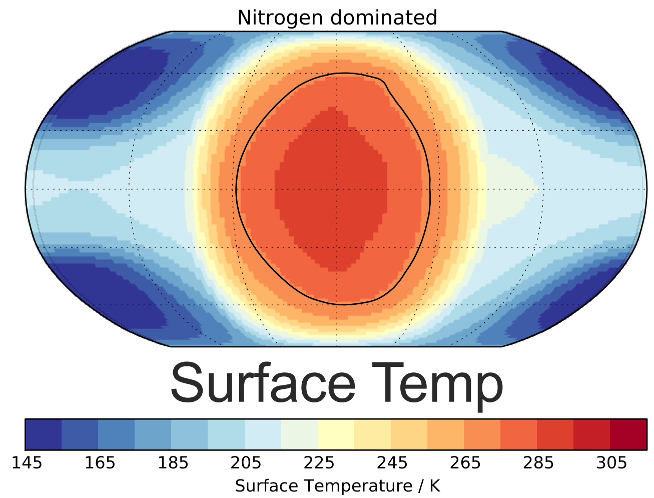


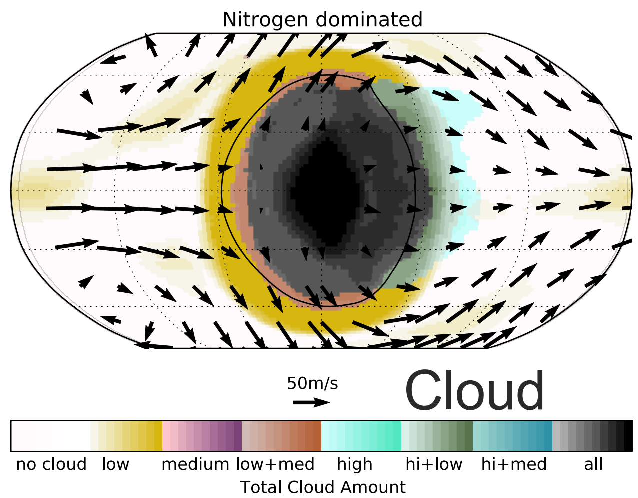


Lines et al. (2018, A&A)

Terrestrial planets

- The holy-grail, but observations currently limited to “it’s this big, in this orbit” – nothing about structure or composition of atmosphere
- Doesn’t stop us speculating!
- E.g. Proxima Centuari B - ~Earth mass planet orbiting our nearest star
- Given an Earth-like atmosphere (N_2, CO_2, H_2O), modelling suggests planet would have temperate climate and liquid water

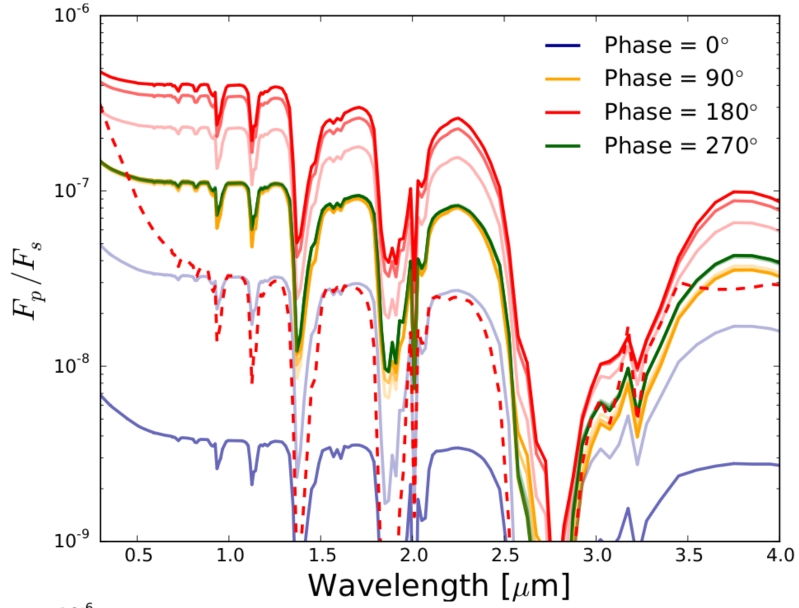


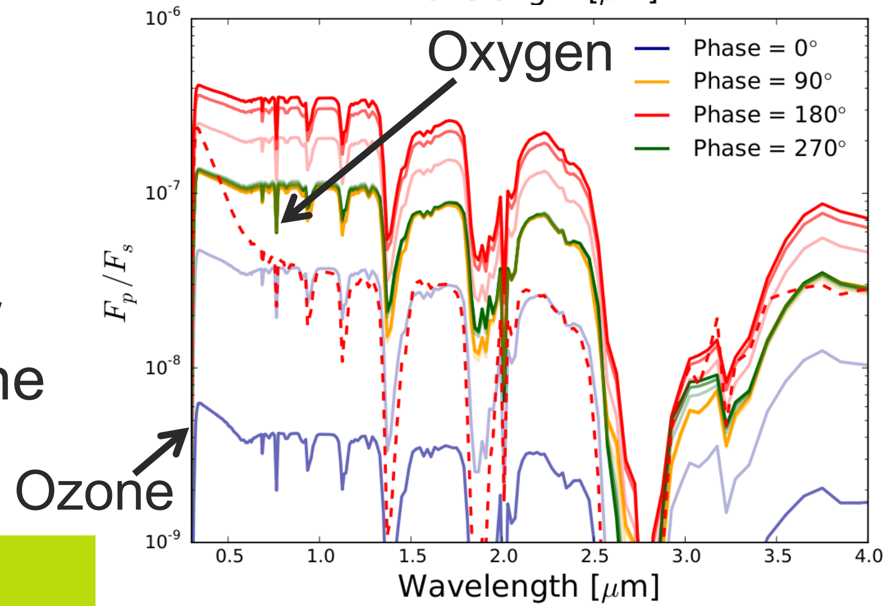


Boutle et al. (2017, A&A)

How might we know?

- Plenty of interesting science that can be done studying the climate of such a planet
- Key question though is how would we ever know?
- Again, can produce simulated observables (the kind that could be possible with future telescopes).
- Small changes to the atmosphere can show up the signals of important gases, e.g. Ozone and Oxygen





Boutle et al. (2017, A&A)

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Conclusions

The same (very large) code can be used for highly detailed simulations of small parts of this planet, to planetary scale simulations of gas-giants many light years away

Efficiency is a key driver – we're always doing the best we can with the computer time we have available

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