Self-organised convection in a cloud-resolving model: realistic and idealistic simulations

mpipks
Nonlinear Time Series Analysis

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Outline

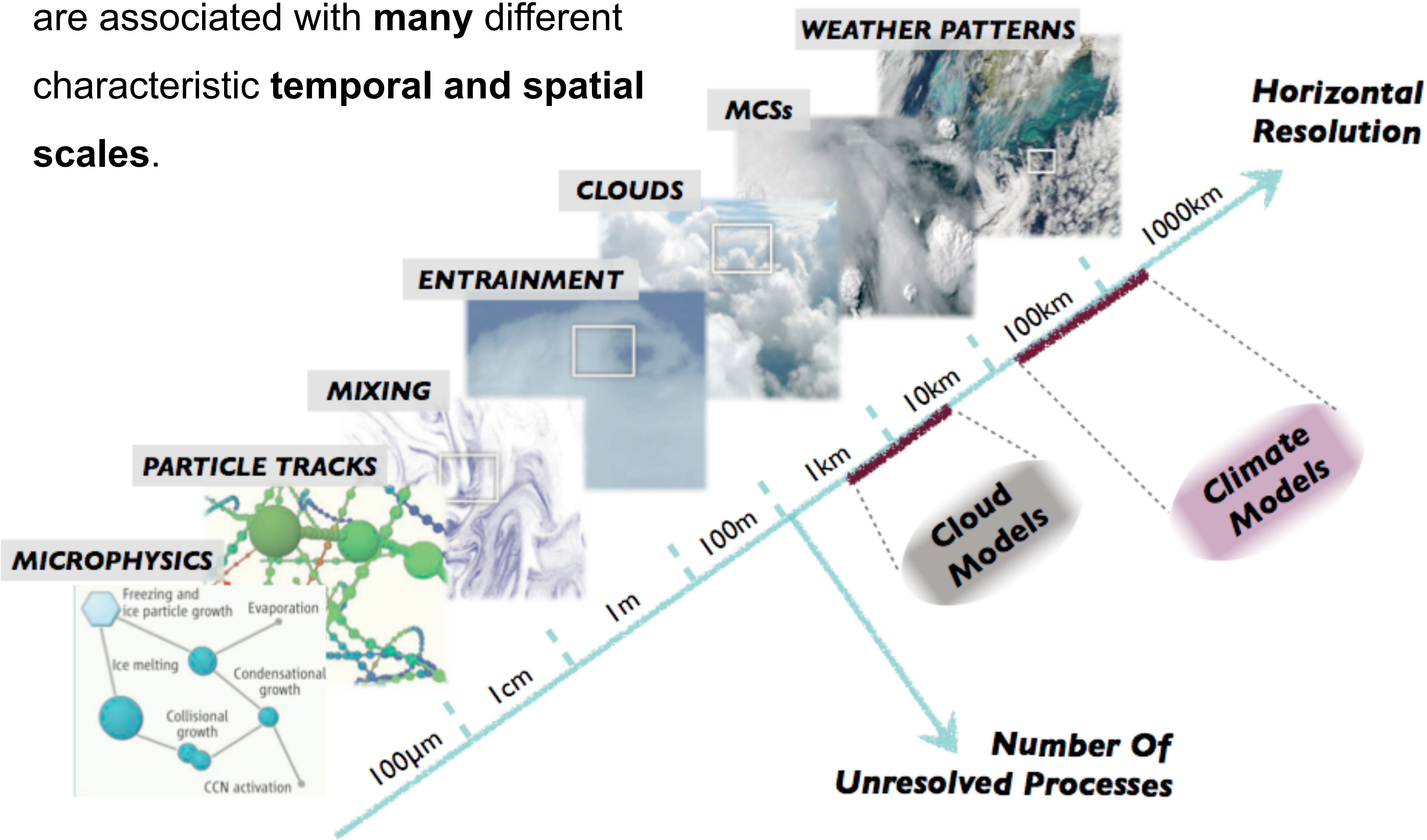
- Motivation - atmospheric convection and precipitation
- Observational studies - Criticality and rainfall
  - Surprises in Cloud resolving models:

    convection self-aggregates (under some conditions)
- Looking at idealised vs realistic runs
- Conclusions, references and outlook

Convection and precipitation

Processes relevant for precipitation are associated with **many** different characteristic **temporal and spatial scales**.

[Adaption from E. Bondenschatz *ETAL*, Science (2010)]



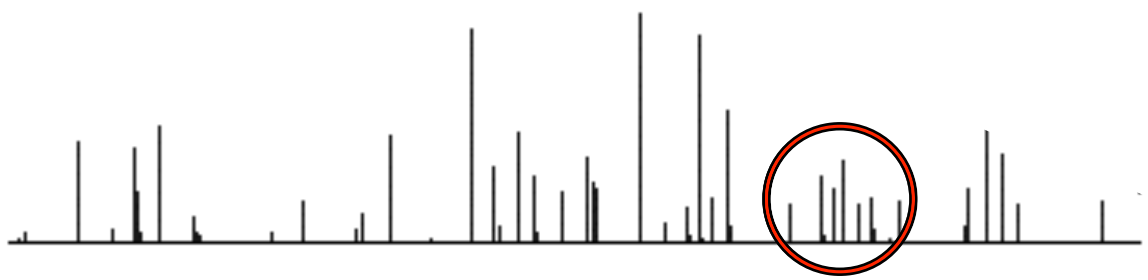
Why clouds and precipitation are important

- Convection and precipitation are a key for Earth's climate.
- Leading role in: planetary heat, moisture and momentum budgets.
- Errors in its parametrization are related to major issues in climate modelling: equatorial waves or complex atmospheric oscillations such as the Madden-Julian oscillations, day cycle.
- Uncertainty about whether many regions will get wetter or drier.
- Its understanding is a prerequisite for adequate forecasts of damaging flash-flood events.
- Genesis of tropical cyclones is still not well understood, or how climate change will affect them.
- Modelling of convection is high-priority societal issue.

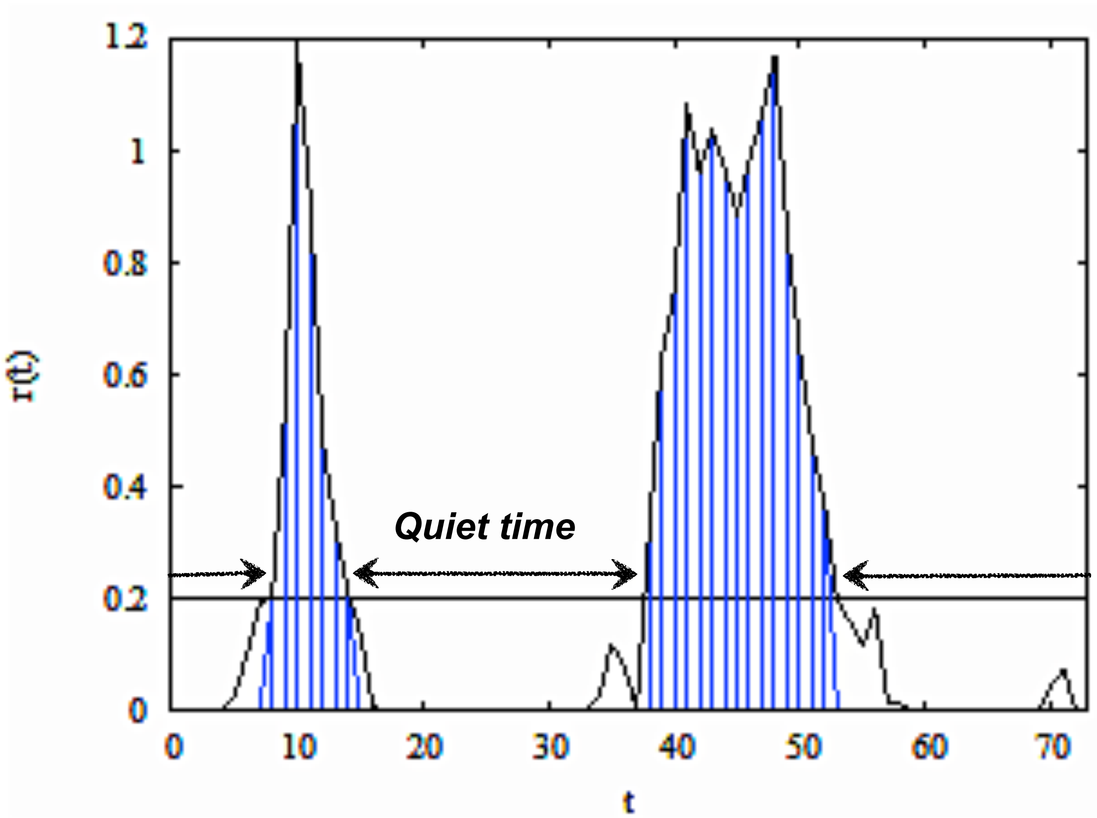
Looking at local observations

Universal Statistical Properties

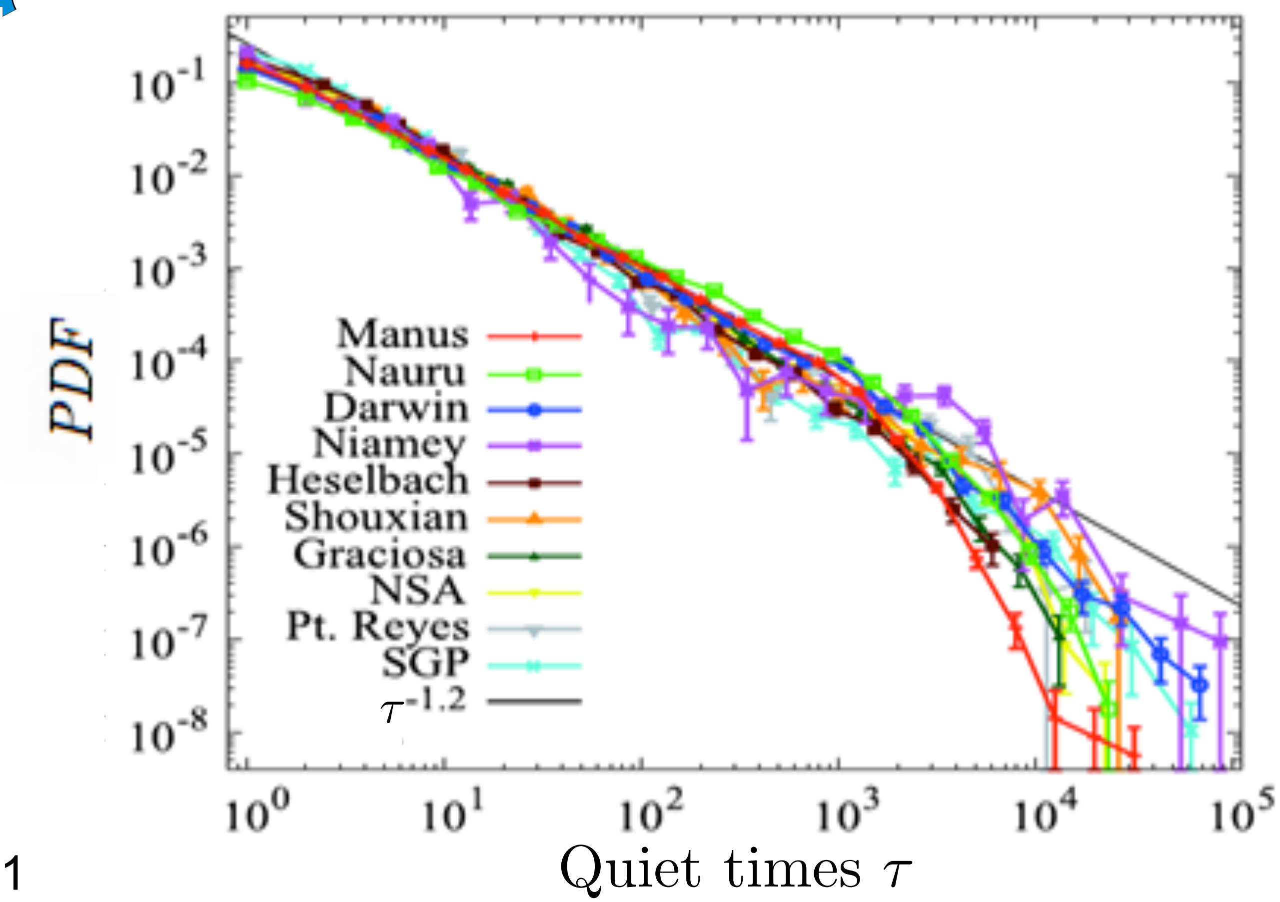
Rain rate time series, **1-minute resolution**.



Rain event definition



Quiet time distribution



Peters, Deluca, Corral, Holloway and Neelin, JSTAT 2011

What can be underlying a Power-law distribution?

- Exponentiation of the Exponential
- Inverse of a random variable
- The Yule process or ‘the richer gets richer’
- Random walk
- Percolation
- Branching process
- Self-organised criticality
- Sweeping the instability
- Among others....

SOC expectations: Finite Size Scaling

For SOC models, moments of the avalanche size distributions scale with the system size L like

$$< s^k > \propto L^{D(1+k-\alpha)} \text{ for } k > \alpha - 1,$$

where the exponent D is called the avalanche dimension, and the exponent α is called the avalanche size exponent.

Moreover, the avalanche size distribution taking into account the finite size effects can be described as

$$P(s) = s^{-\alpha} G(s/s_\xi) \quad \text{for} \ \ s > s_l,$$

where $s_\xi = L^D$ and $G(x)$ is a scaling function s. t.

$$G(x) = \begin{cases} \text{a constant} & \text{if } x \ll 1 \\ \text{decays very fast} & \text{if } x > 1 \end{cases} .$$

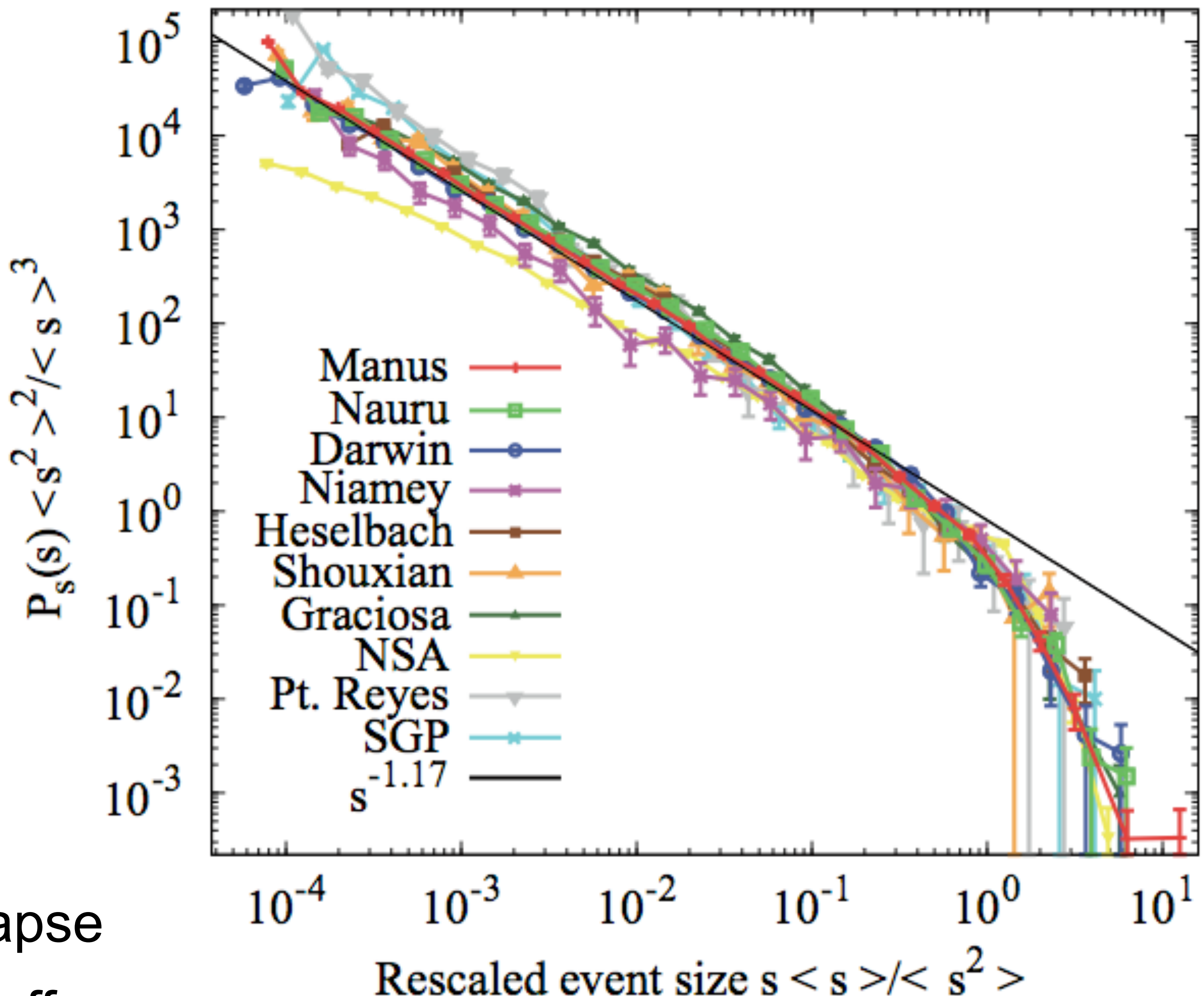
Data Collapse

The effective size of the system is proportional to a appropriate ratio of moments

$$s_\xi \propto \frac{< s^2 >}{< s >} \text{ if } s_l \ll s_\xi$$

and

$$s_\xi^\alpha \propto \frac{< s^2 >^2}{< s >^3}.$$



Rescaling the x-axis we collapse the loci of the large-scale cutoffs and in y-axis we shift the distributions along their supposed power laws.

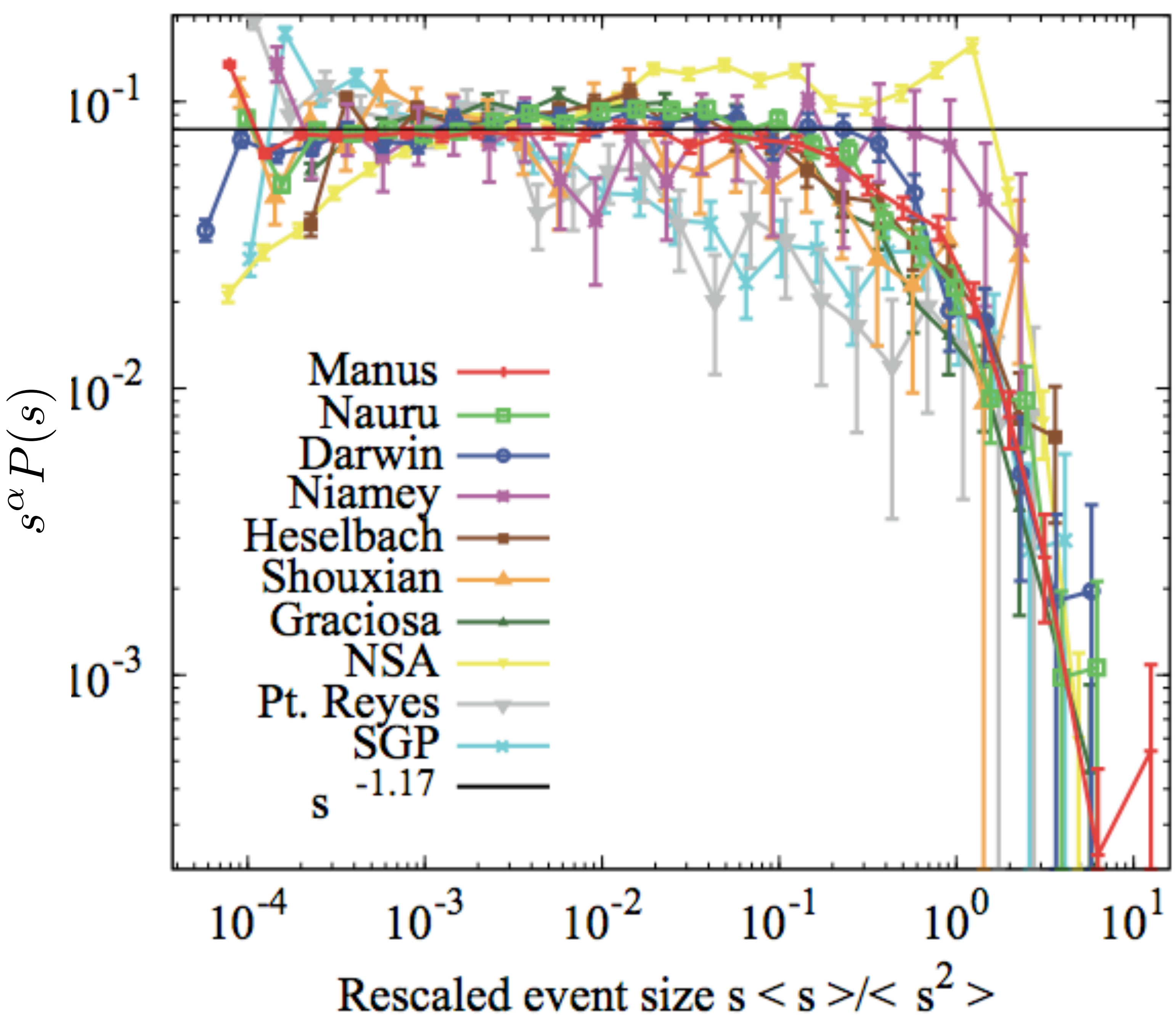
The Scaling Function

Then, with an estimate of the exponent, the scaling function

$$G(s/s_\xi)$$

can be visualized plotting

$$s^\alpha P(s) \text{ vs } s< s >/< s^2 >.$$

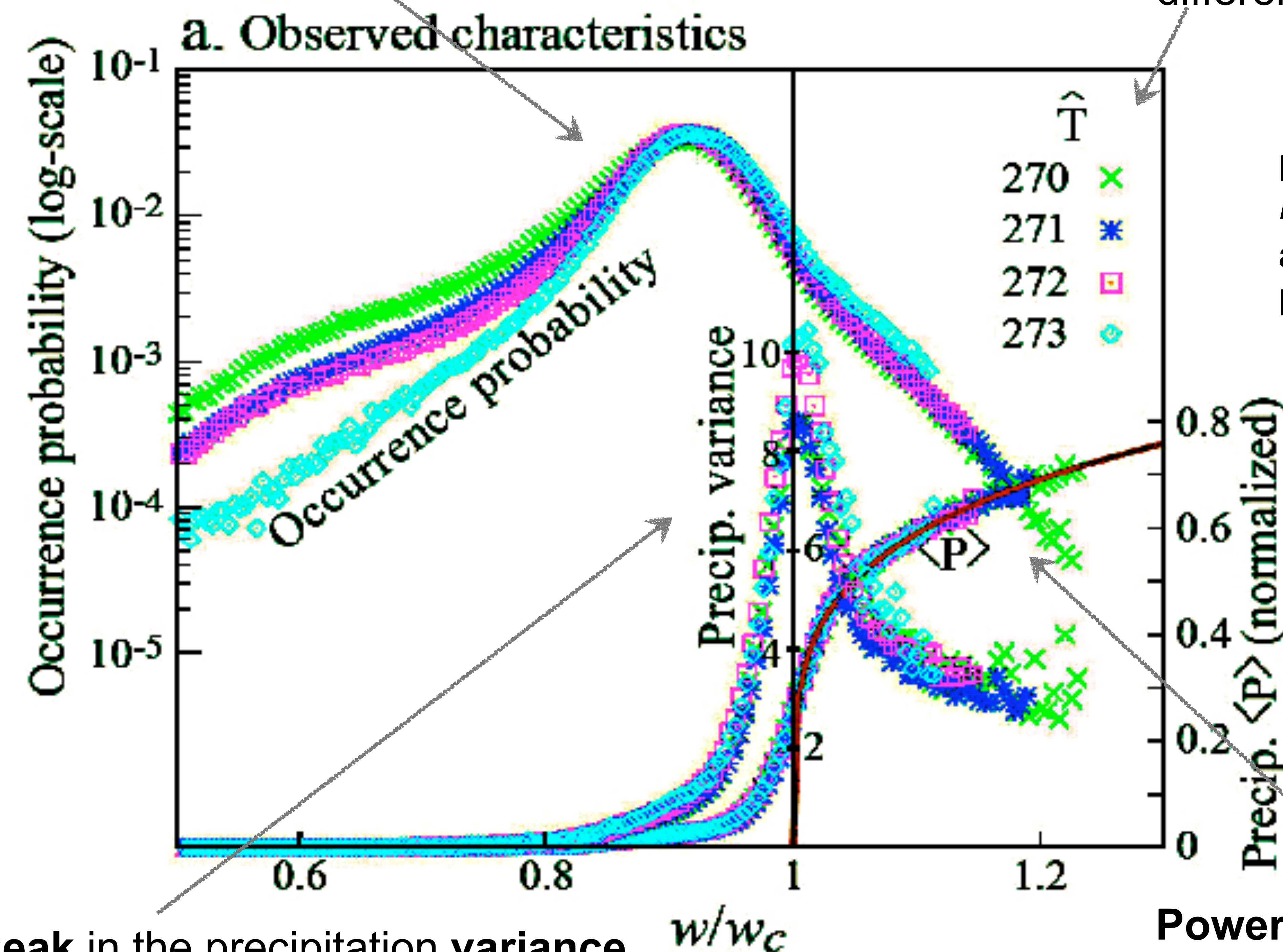


Looking at satellite observations

Sharp transition in precipitation at a critical value of water vapor

Attractive transition: the system tends to be near the transition to strong convection

Data **collapse** for different temperatures



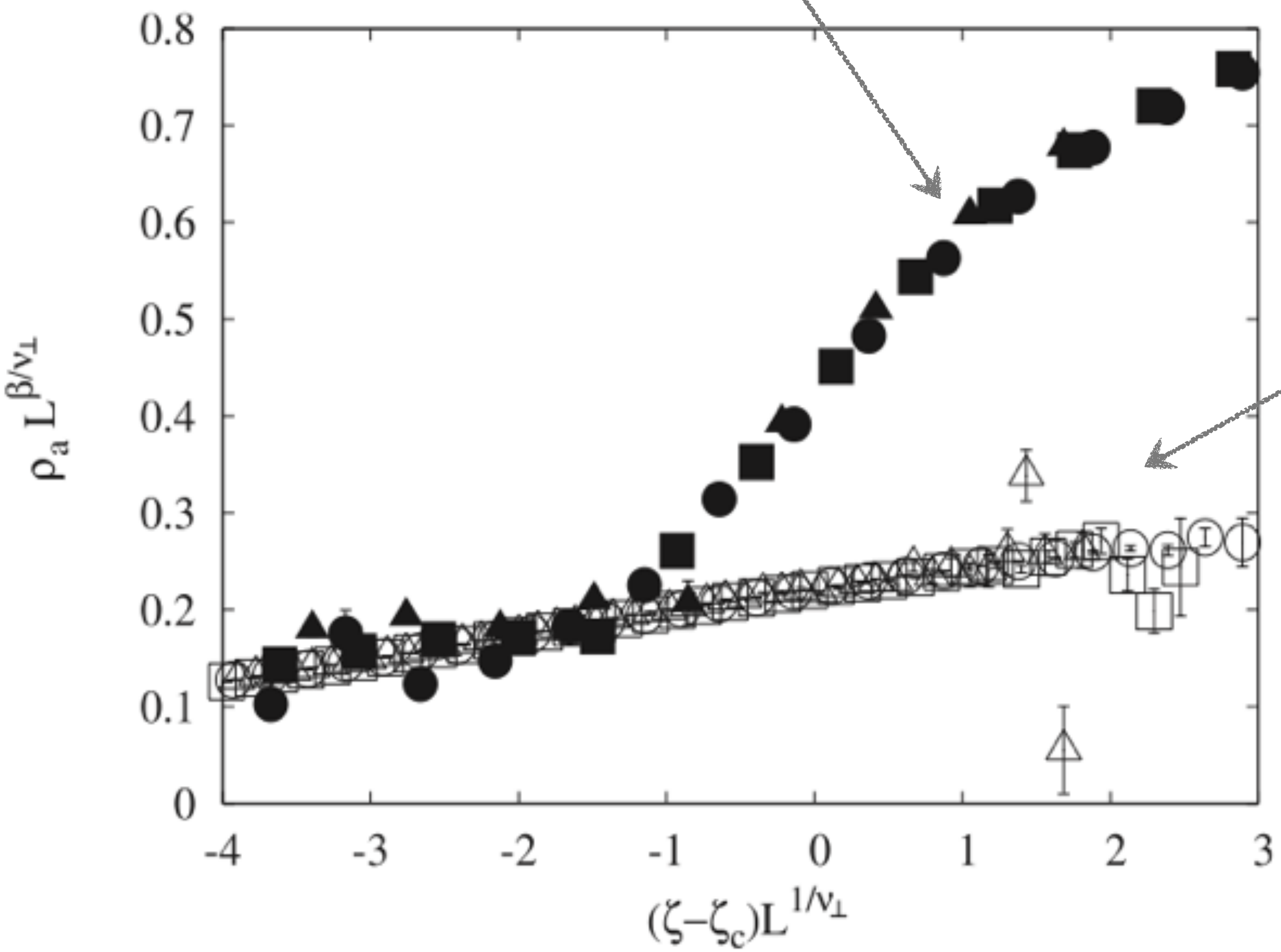
Peters & Neelin, *Nature Phys.* (2006) and Neelin ETAL (2008)

Peak in the precipitation **variance**.

Power law pick-up of precipitation

Pruessner and Peters, 2012

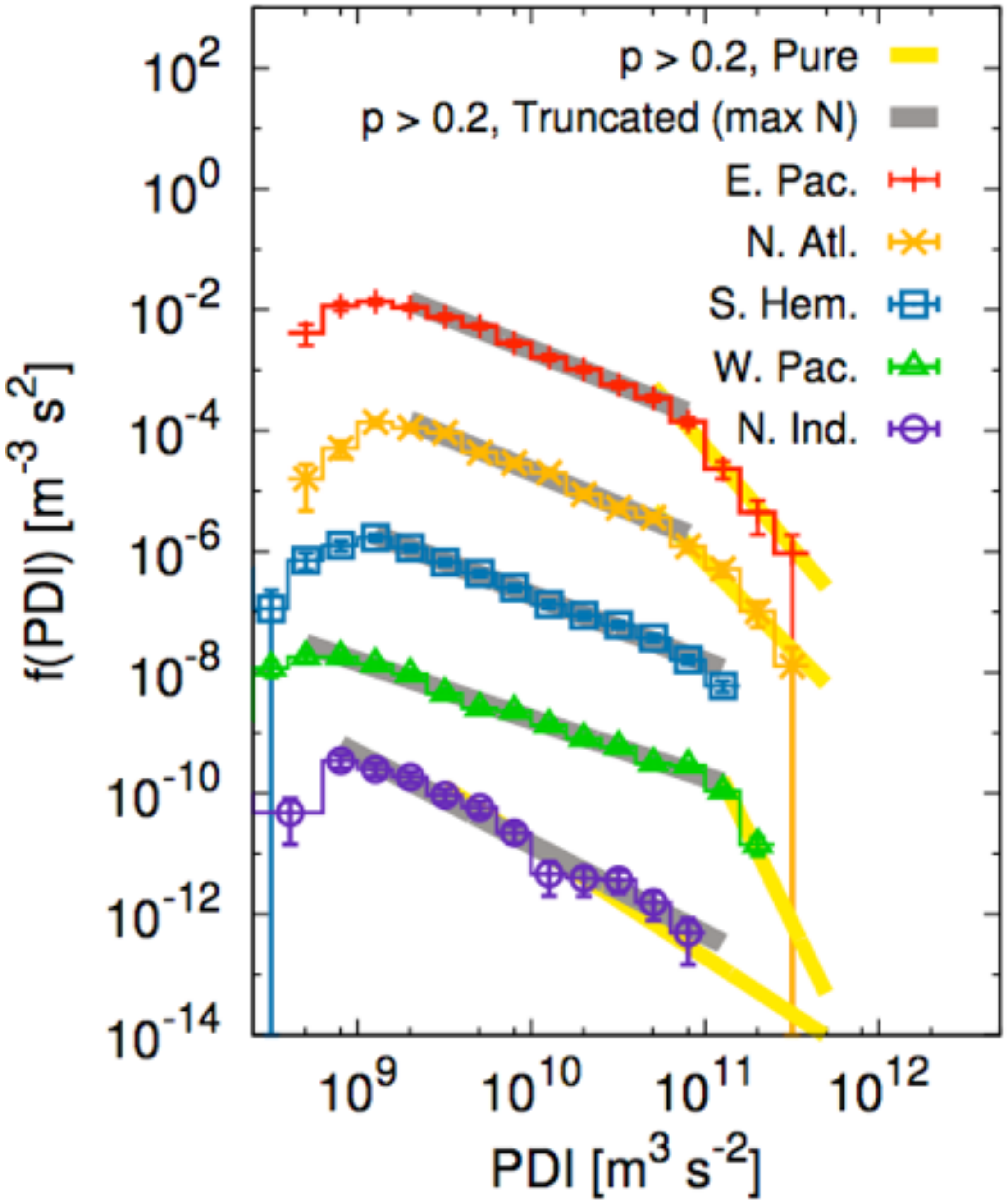
For small lattice size, L=20, and controlling the particle density!



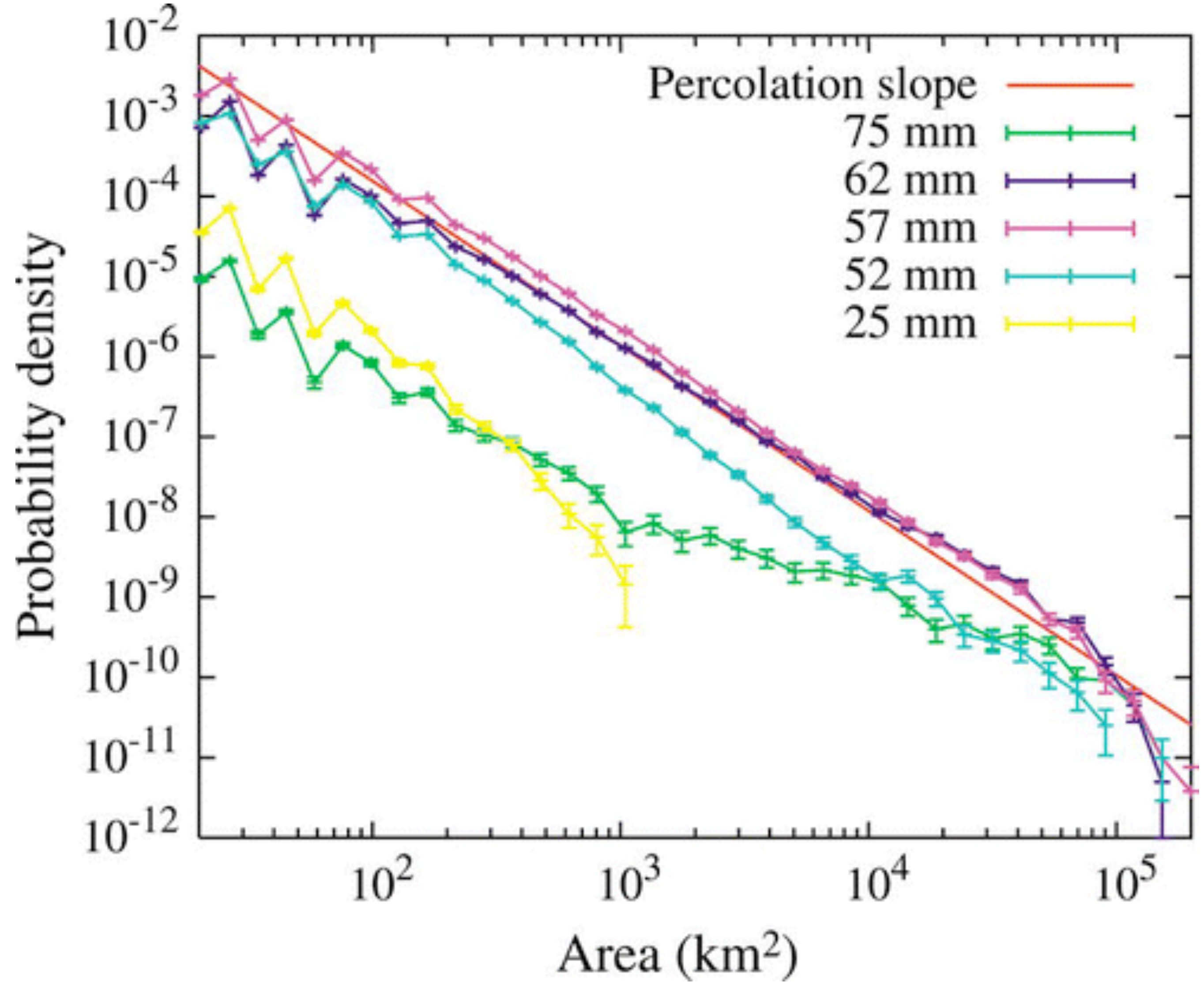
For higher lattices sizes (void symbols), and without controlling the particle density we cannot see anything.

That's not a good way to look if the SOC analogy is good or not.

Hurricane Energy Dissipation



Mesoscale Convective Cluster Sizes Distributions



From Peters et al, J. Atmos. Sci. 2009

Also long range correlated signals are very often observed.

Looking at simulations

Weather and Climate Models

From the Wikipedia

- Box models

simplified versions of complex systems, reducing them to boxes (or reservoirs) linked by fluxes

- 0-dim models

simple model of the radiative equilibrium of the Earth

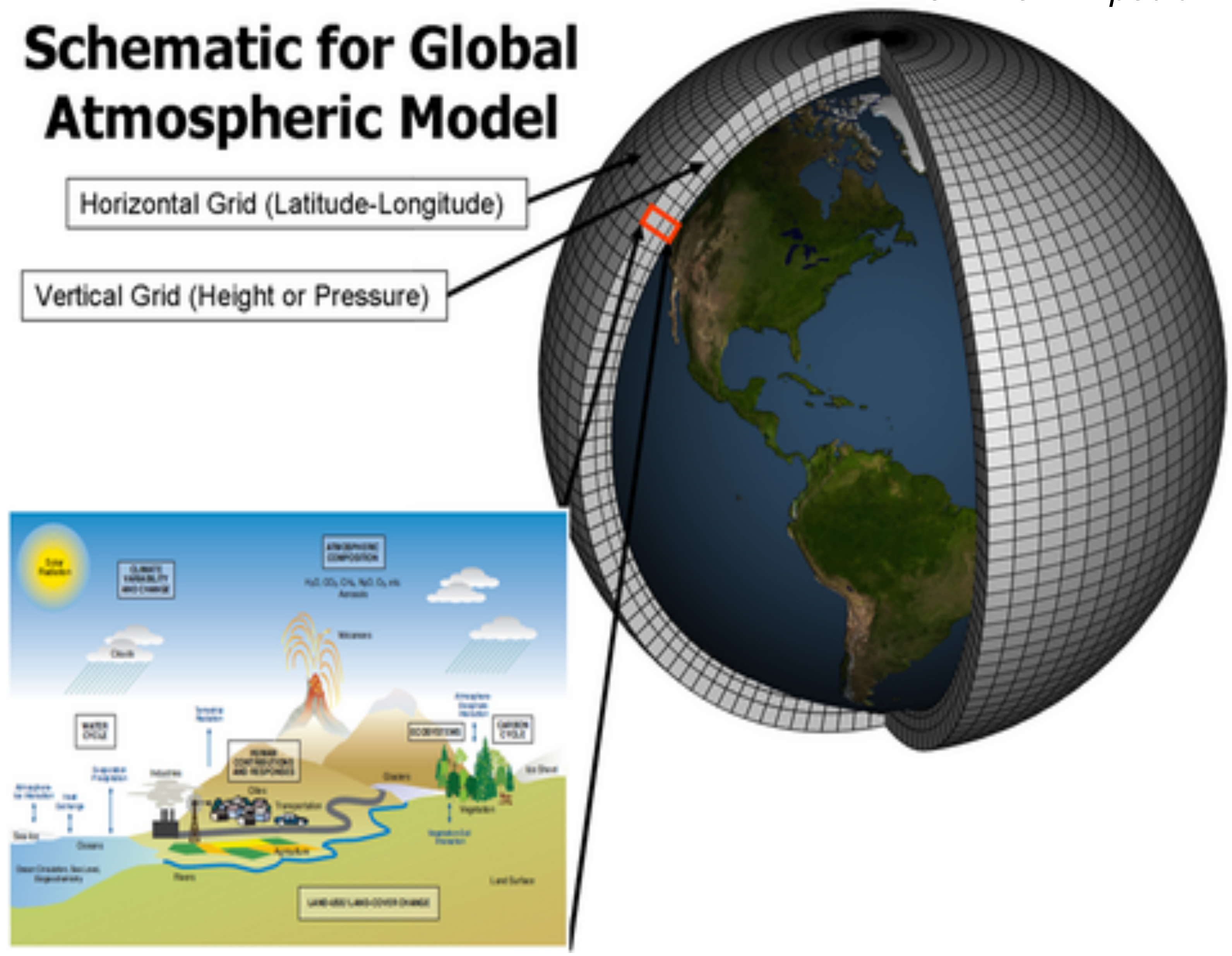
$$(1-a)S\pi r^2 = 4\pi r^2 \epsilon \sigma T^4$$

- Radiative-convective models

considers two processes of energy transport:

- upwelling and downwelling radiative transfer through atmospheric layers that both absorb and emit infrared radiation

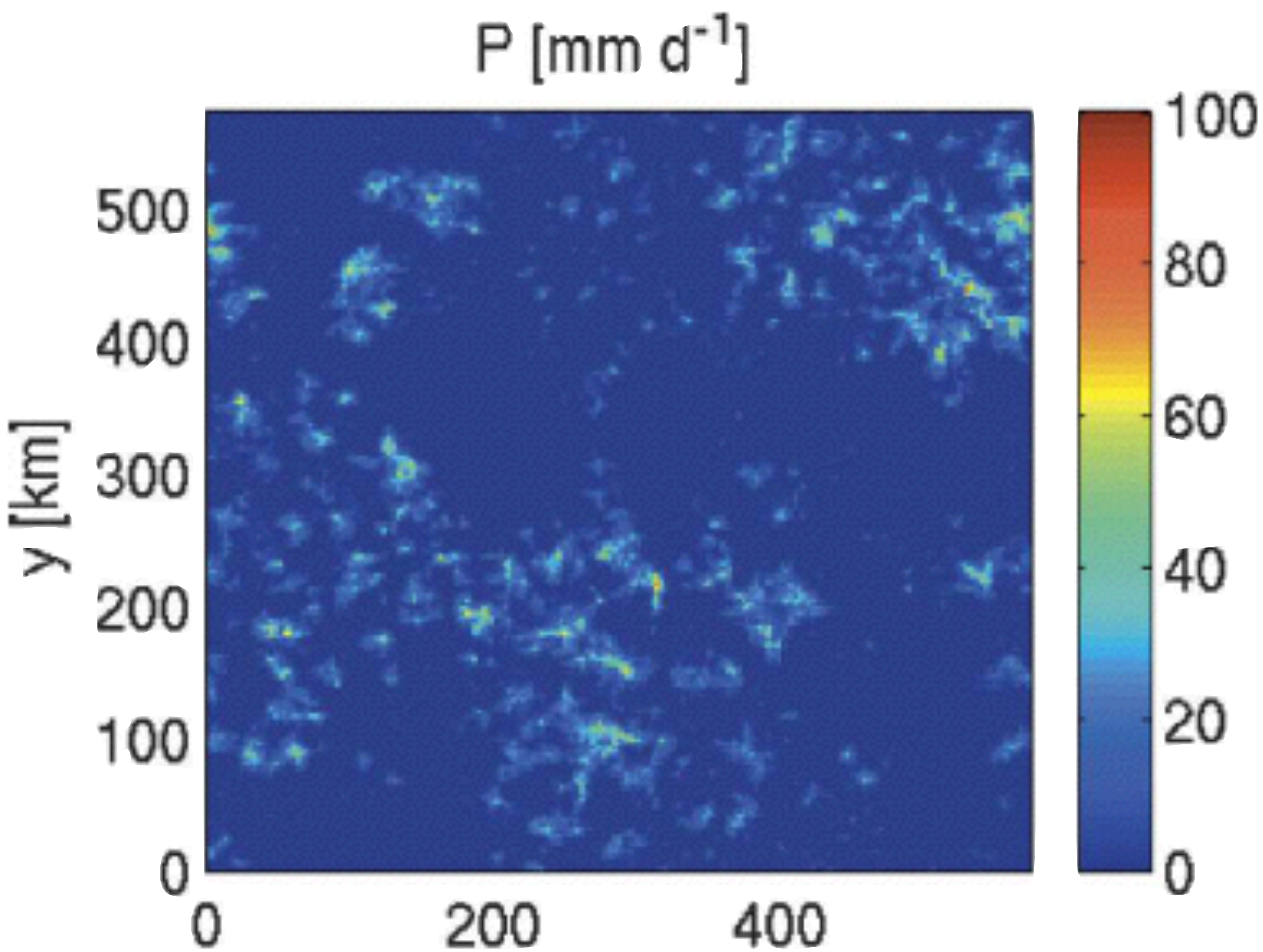
- upward transport of heat by convection

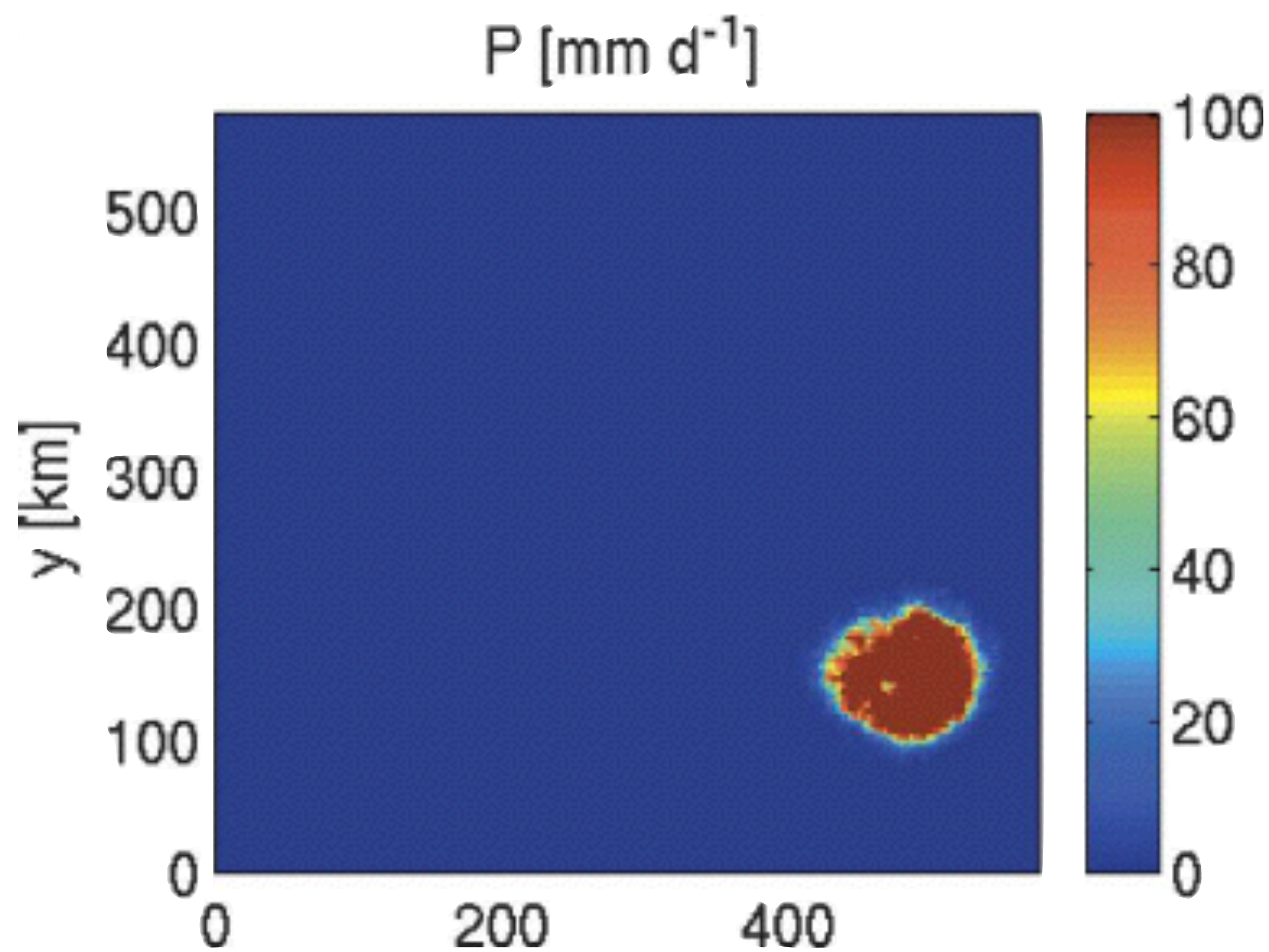


- Higher-dimension models, energy balance models
- EMICs (Earth-system models of intermediate complexity)
- Cloud Resolving Models
- GCMs (global climate models or general circulation models)

An interesting surprise?

Cloud-system-resolving models used to the simplest form of Quasi-equilibrium (effects of large-scale circulation on convection ignored) in a 3D domain.





From Bretherton et al. (2005)

And if Coriolis force is non-zero…

tropical cyclones!

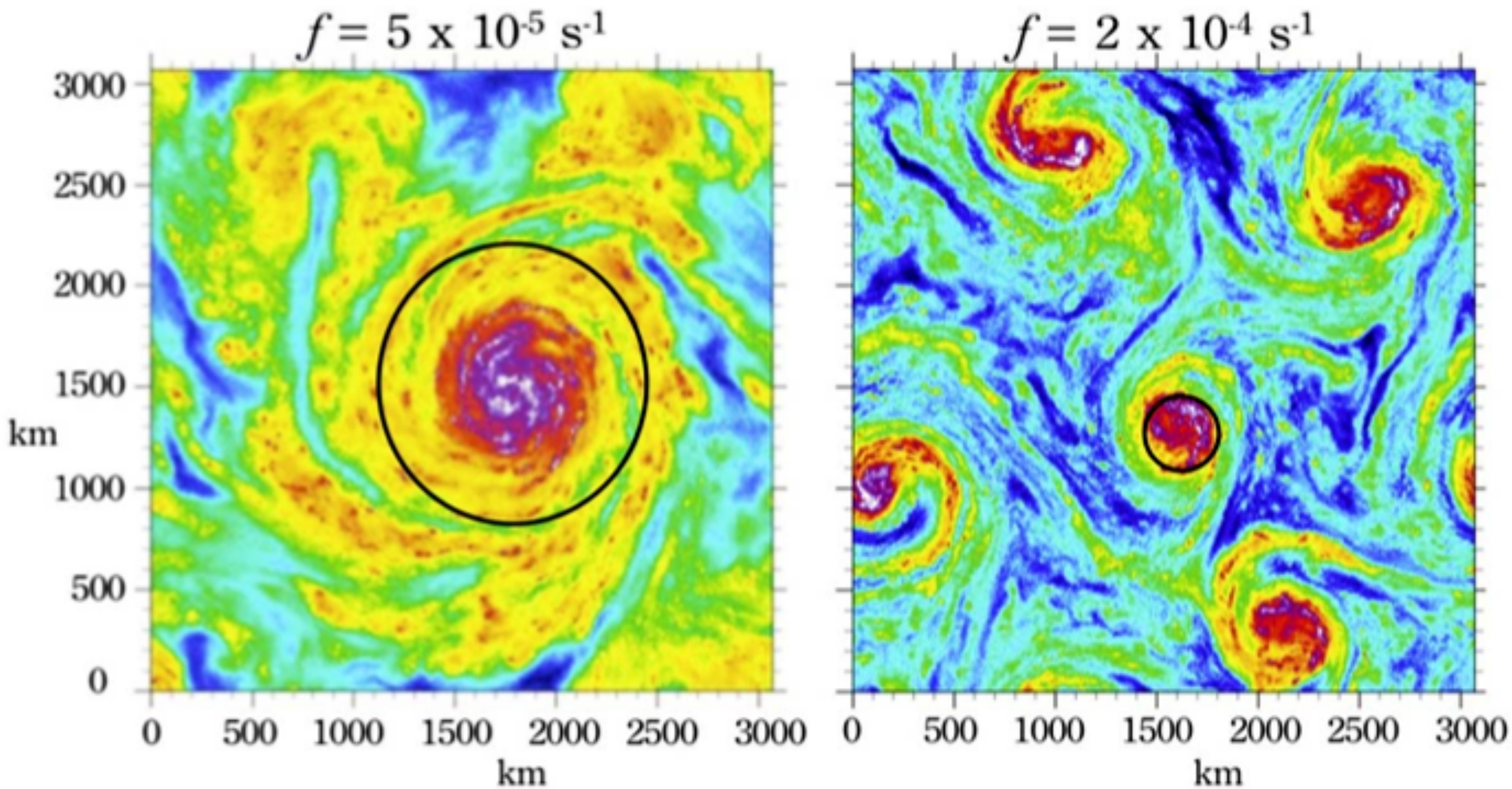


Figure 1. Tropical cyclones for two different values of the Coriolis parameter in otherwise identical RCE simulations (precipitable water is shown; warm colors represent higher values). The black circles on the foreground have diameters computed from formula (1).

from Khairoutdinov and Emanuel 2015 (done by many other peoples well)

consequences of clustering => aggregation dramatically dries up the atmosphere

=> feed-back mechanism?

And the effects of Sea Surface Temperature

all this may have implications for climate change: if Temperature rises convection may tend to aggregate more

Emanuel 2010 ideas of self-organized criticality (SOC) between SST and aggregation state, found aggregation only occurred above about 296 K.

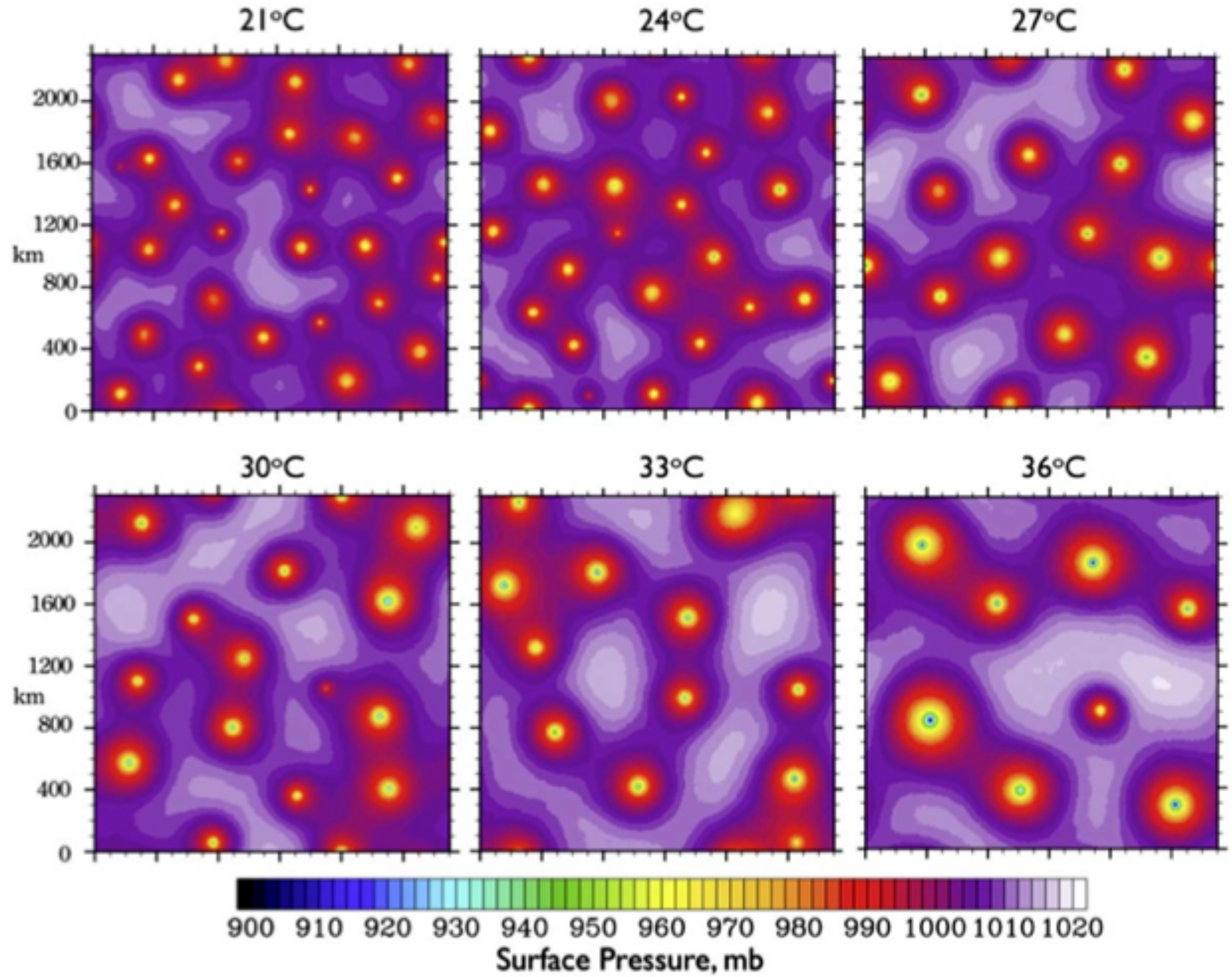


Figure 2. Snapshots of the surface pressure from the *f*-plane RCE simulations for different values of the SST.

from Khairoutdinov and Emanuel 2015

Work from Chris Holloway on UM shows (strong and fast) aggregation down to at least 290 K.

important questions

why and how?

some hints from previous studies:

- it does depends on temperature

- it seems to be very much related to radiation - aggregation dries up the atmosphere which changes how much radiation goes out from the surface to the upper layers of the atmosphere

- Emanuel hypothesises that there is a subcritical bifurcation controlled by Surface Temperature (in his talk @ AGU 2015), with two stable brunches: aggregated/dried out

- is there really self-aggregation? we don’t know which is the mechanism

important questions

is this a real phenomena? if so, which would be its consequences?

- big consequences for climate because it does dry a lot the environment

- it could help us to understand why the climate in the tropics has been so stable (that's a puzzle)

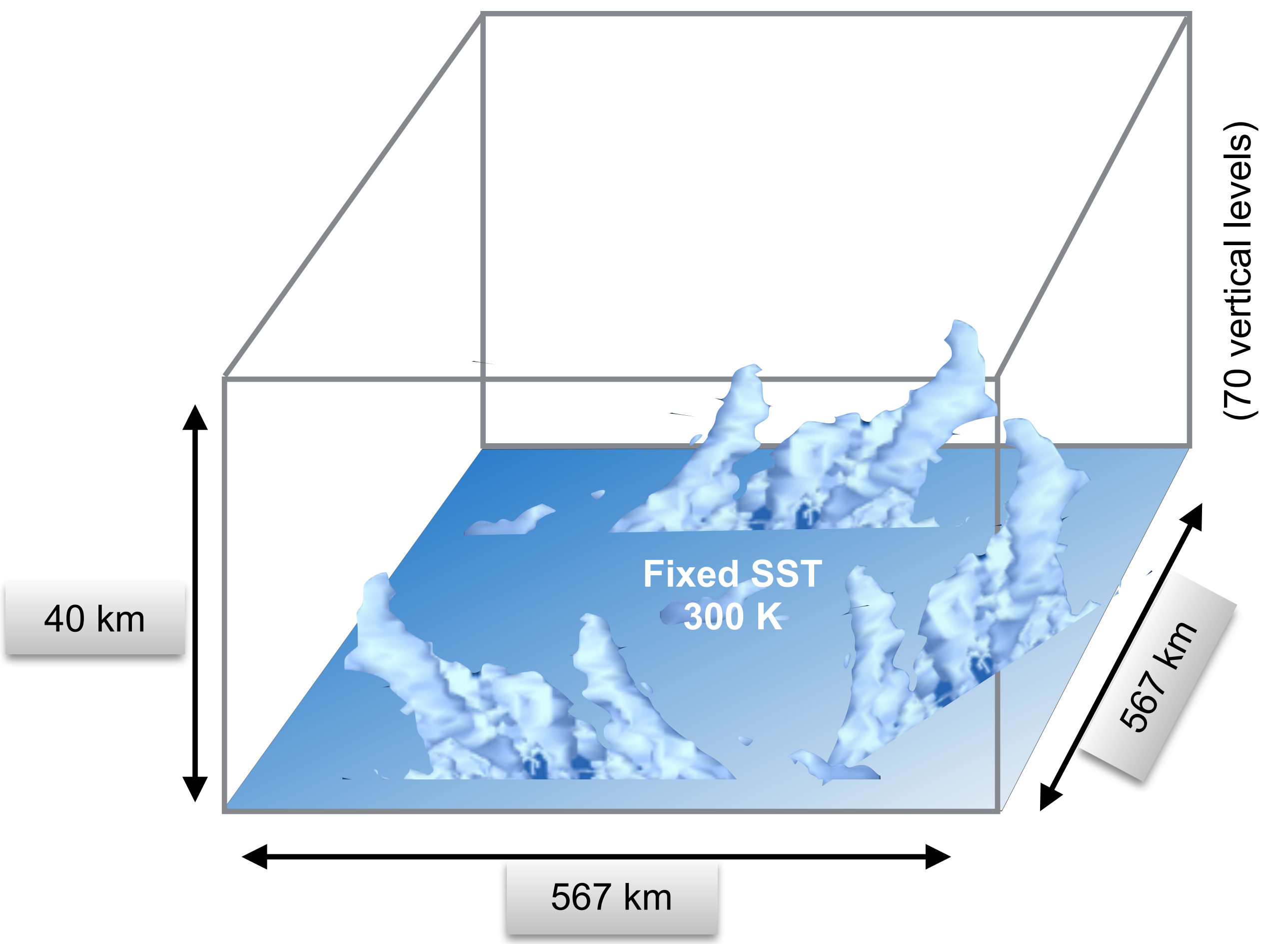
- it can be key for understanding tropical cyclones genesis, to explain its scaling!

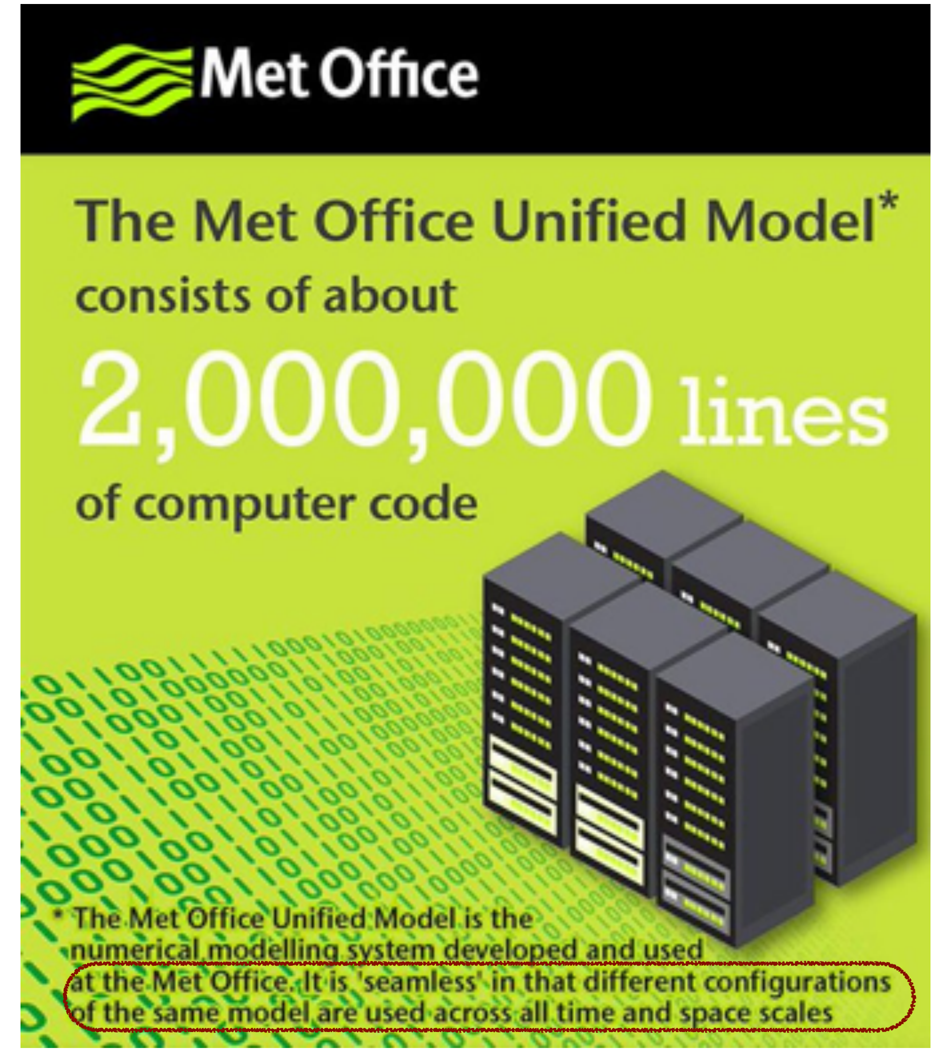
Monsoonal Thunderstorms, Bangladesh and India, July 1985
(taken from a talk of Kerry Emanuel)

Which are the links between convective self-aggregation in idealised models and organised tropical convection in observations or realistic simulations?

Met Office Unified Model

Chris Holloway runs in a supercomputer in Edimburgh…



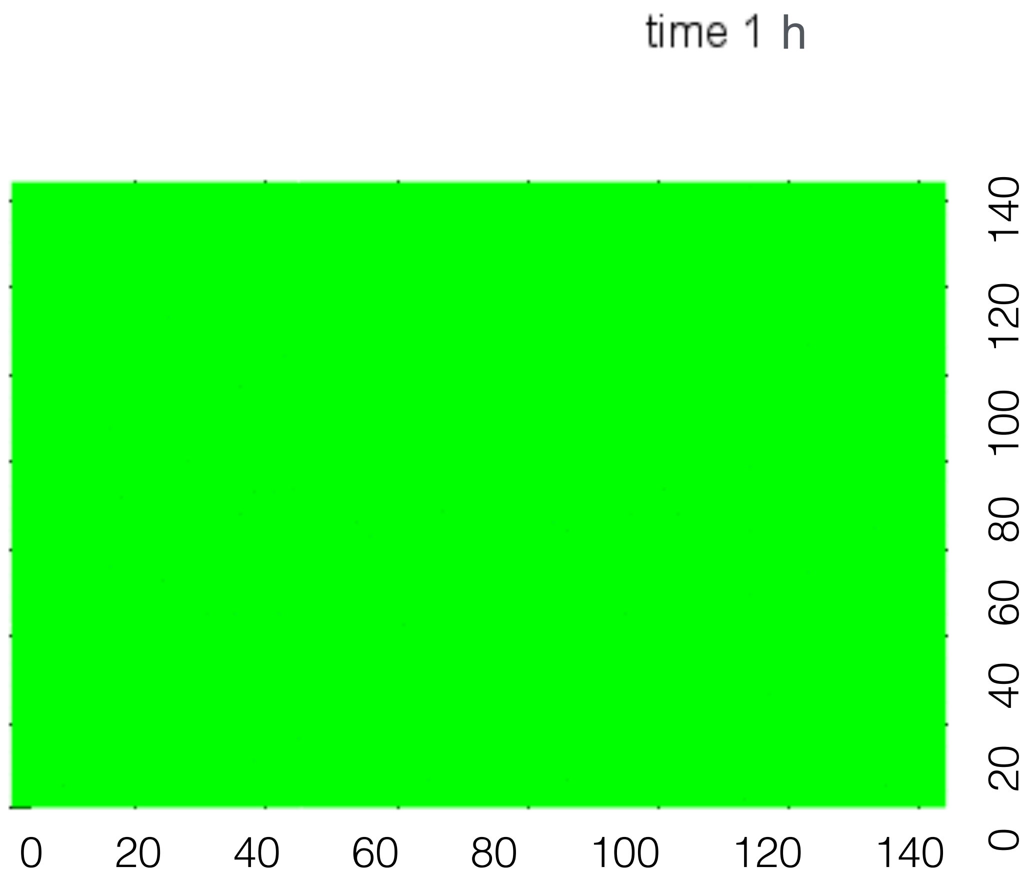


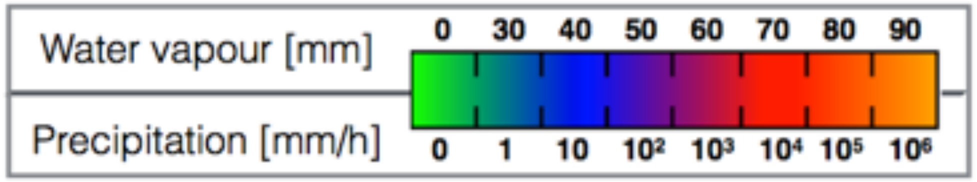
version 7.5 of the Met Office Unified Model

- semi-Lagrangian and non-hydrostatic.
- Smagorinsky-type sub-grid mixing in the horizontal and vertical dimensions
- mixed-phase microphysics scheme with three components: ice/snow, cloud liquid water, and rain.

Almost all rainfall is generated explicitly (no parametrization).

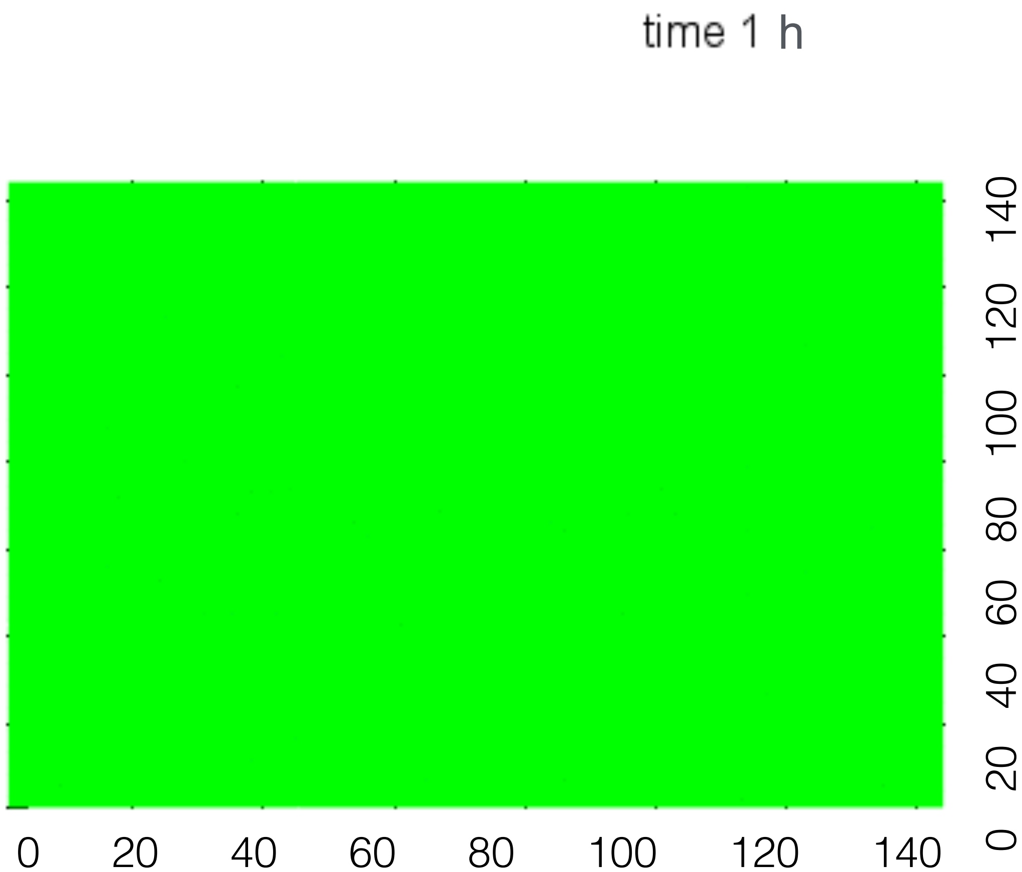
rain rate [mm/h]



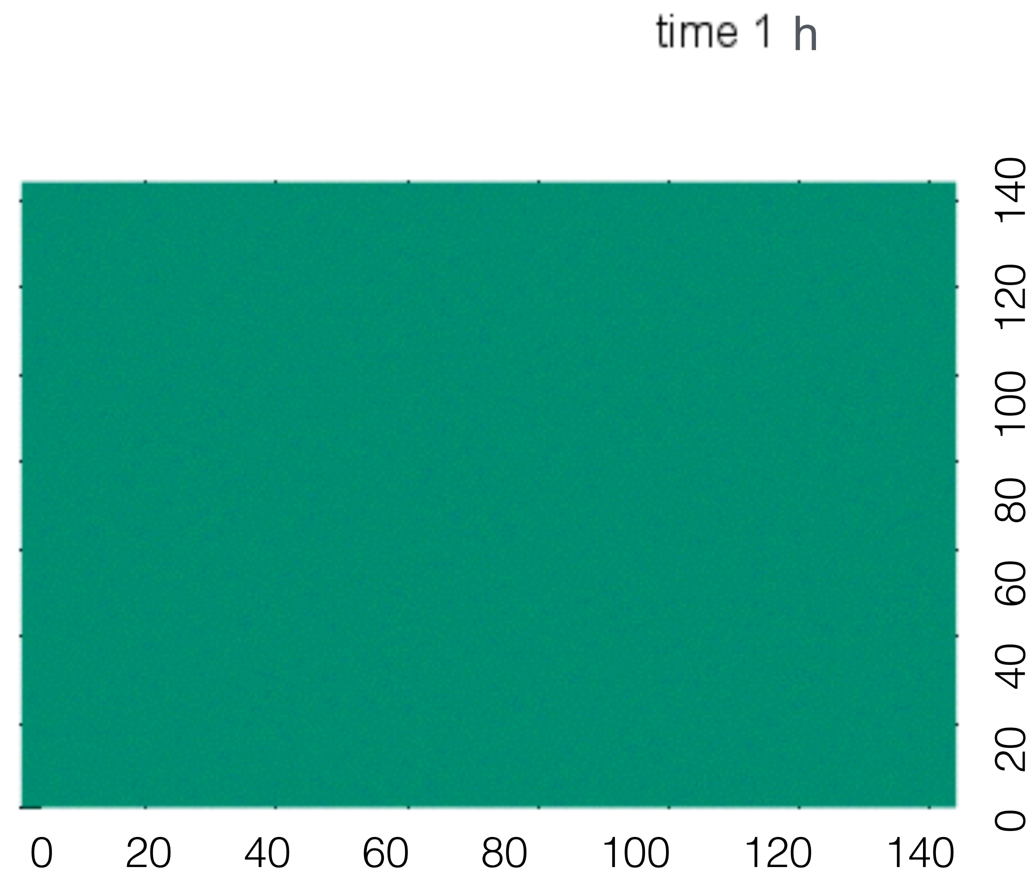


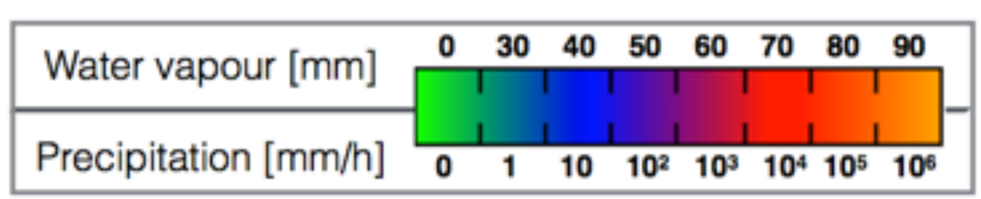
An idealised case

rain rate [mm/h]



water vapour [mm]

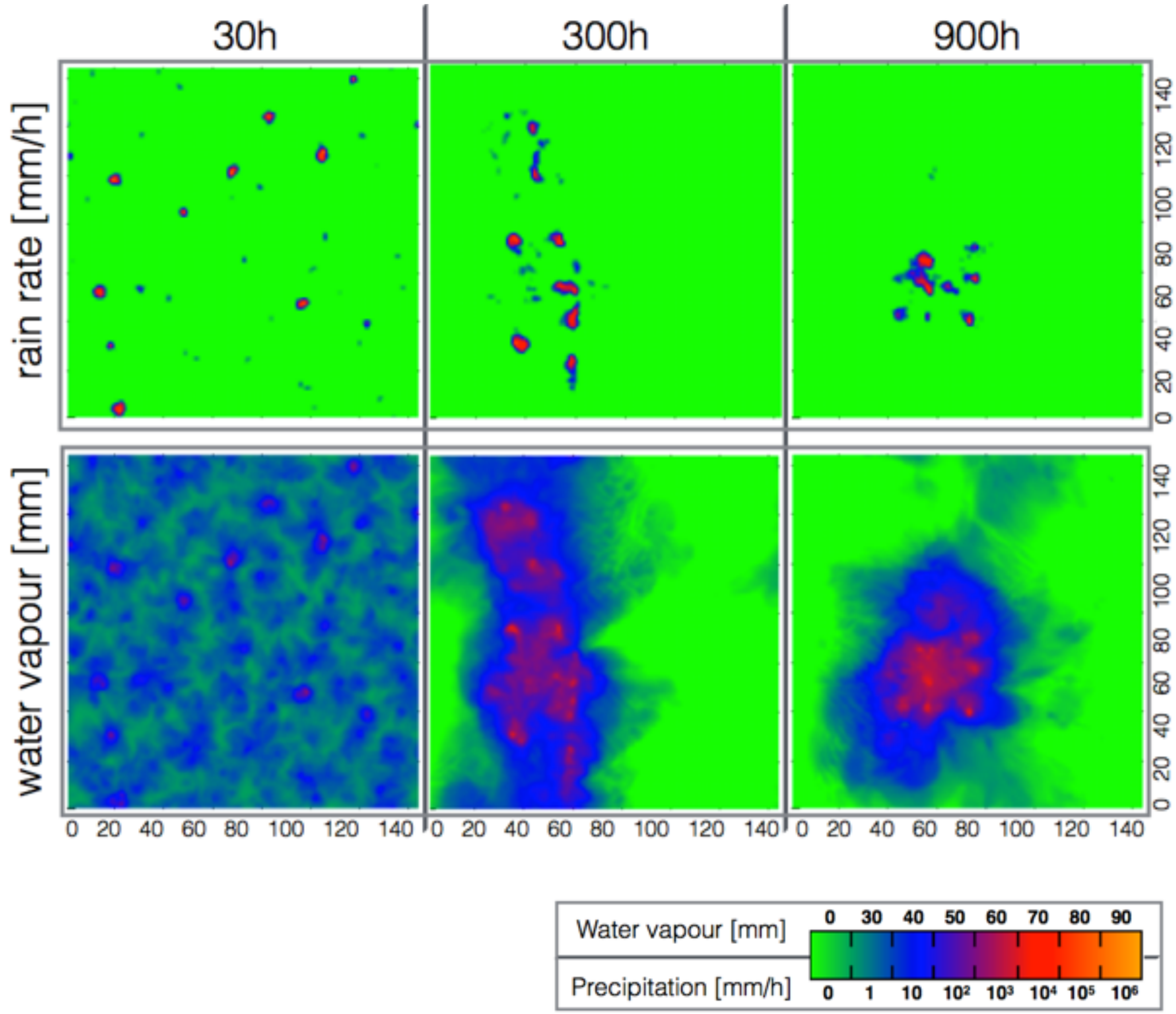




Run A: Idealised control run

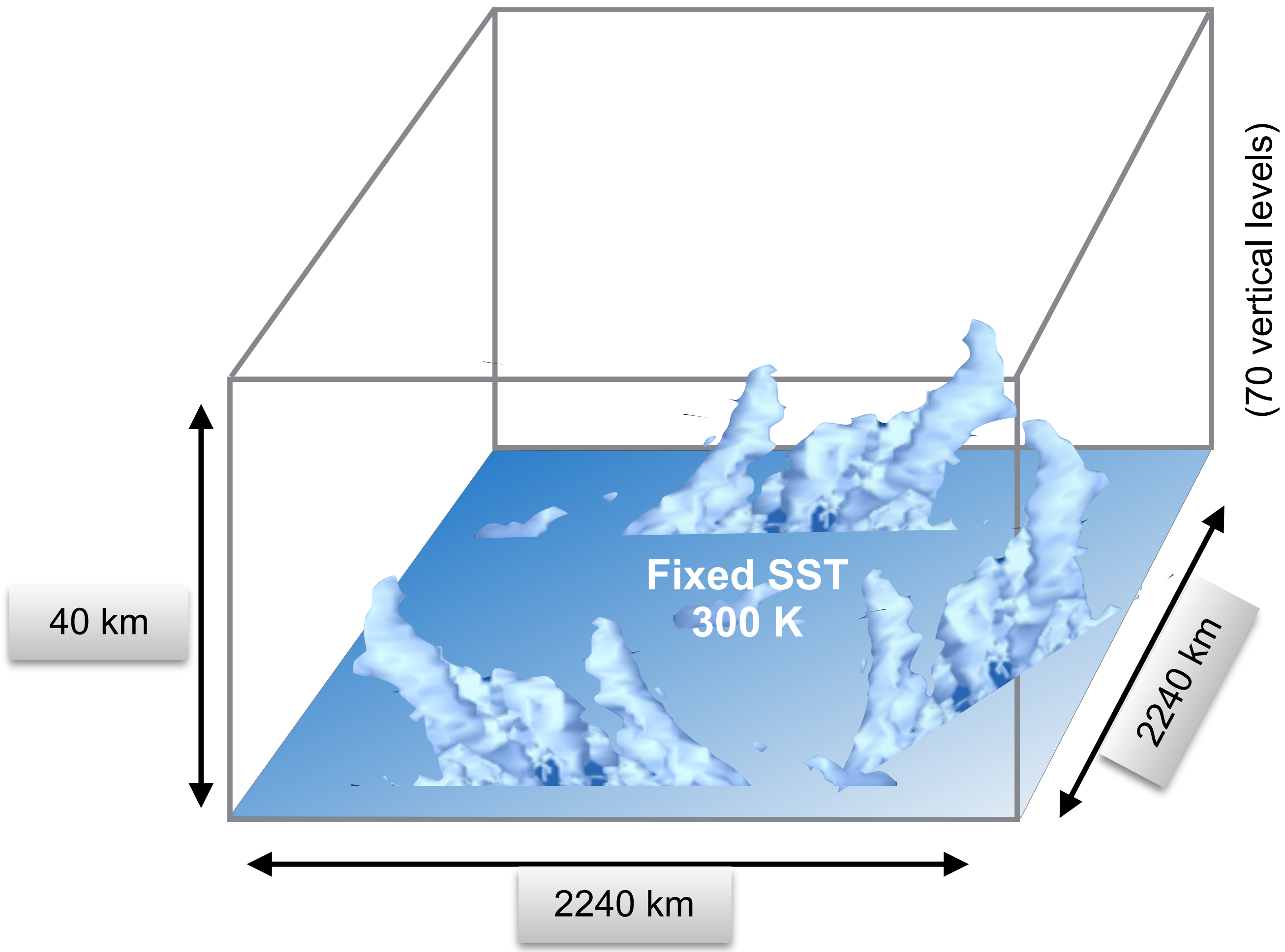
This case is an idealised control run with

- the Radiative-Convective Equilibrium setup (effects of large-scale circulation on convection ignored)
- with fix SST to 300K and
- no rotation
- domain size 576 x 576 km
- periodic lateral boundary conditions
- run for 40 days



More realistic cases

We also analyse real cases of organised convection that resemble the idealised setup. The domains are larger but the simulations are shorter (15 days).



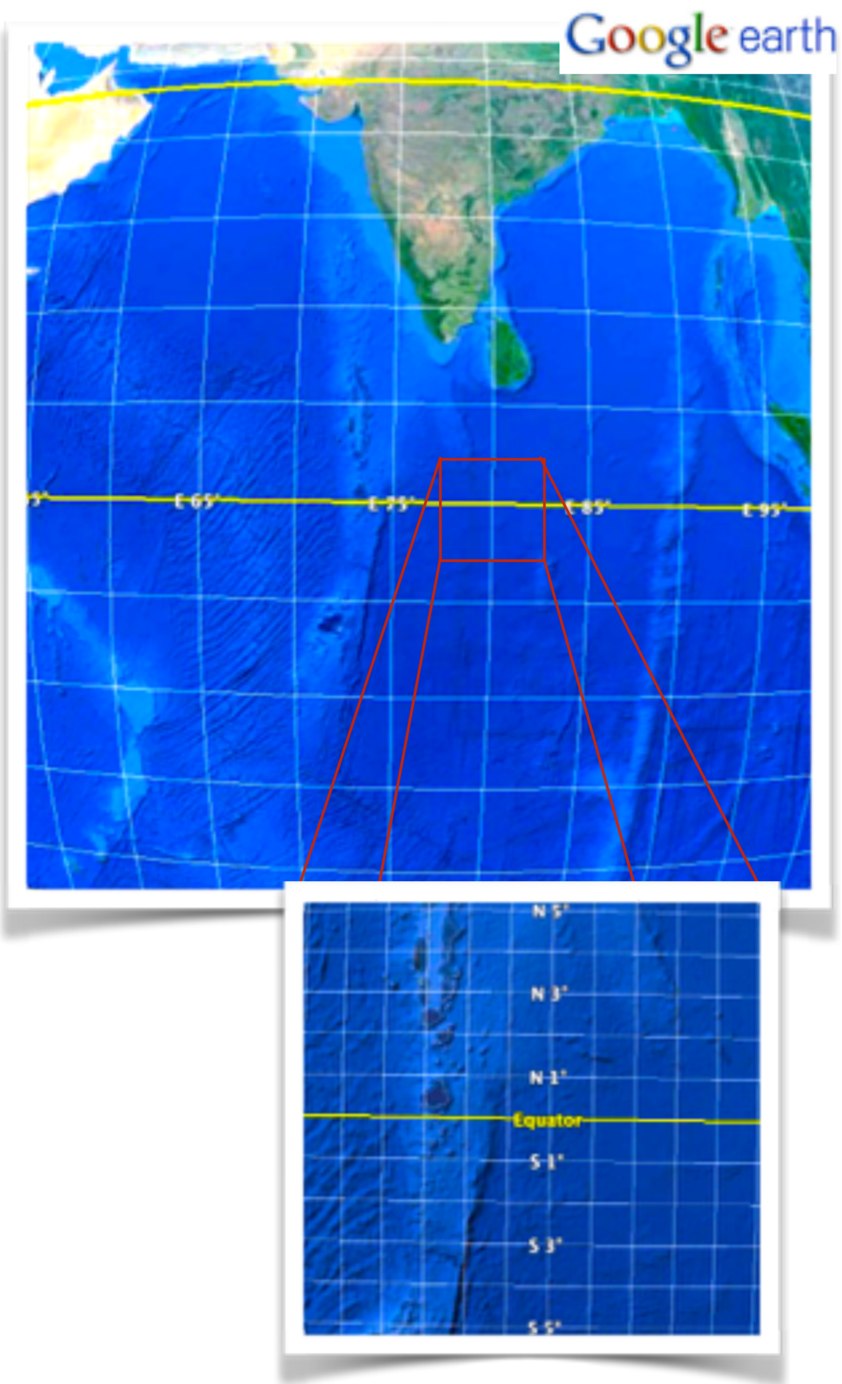
- centered on the equator where rotation effects are at a minimum;
- have an aggregated (highly clustered) state within at least the middle 5 days of the 15-day simulation but still significant mean rainfall during that time;
- sufficiently warm sea surface temperatures (SSTs).

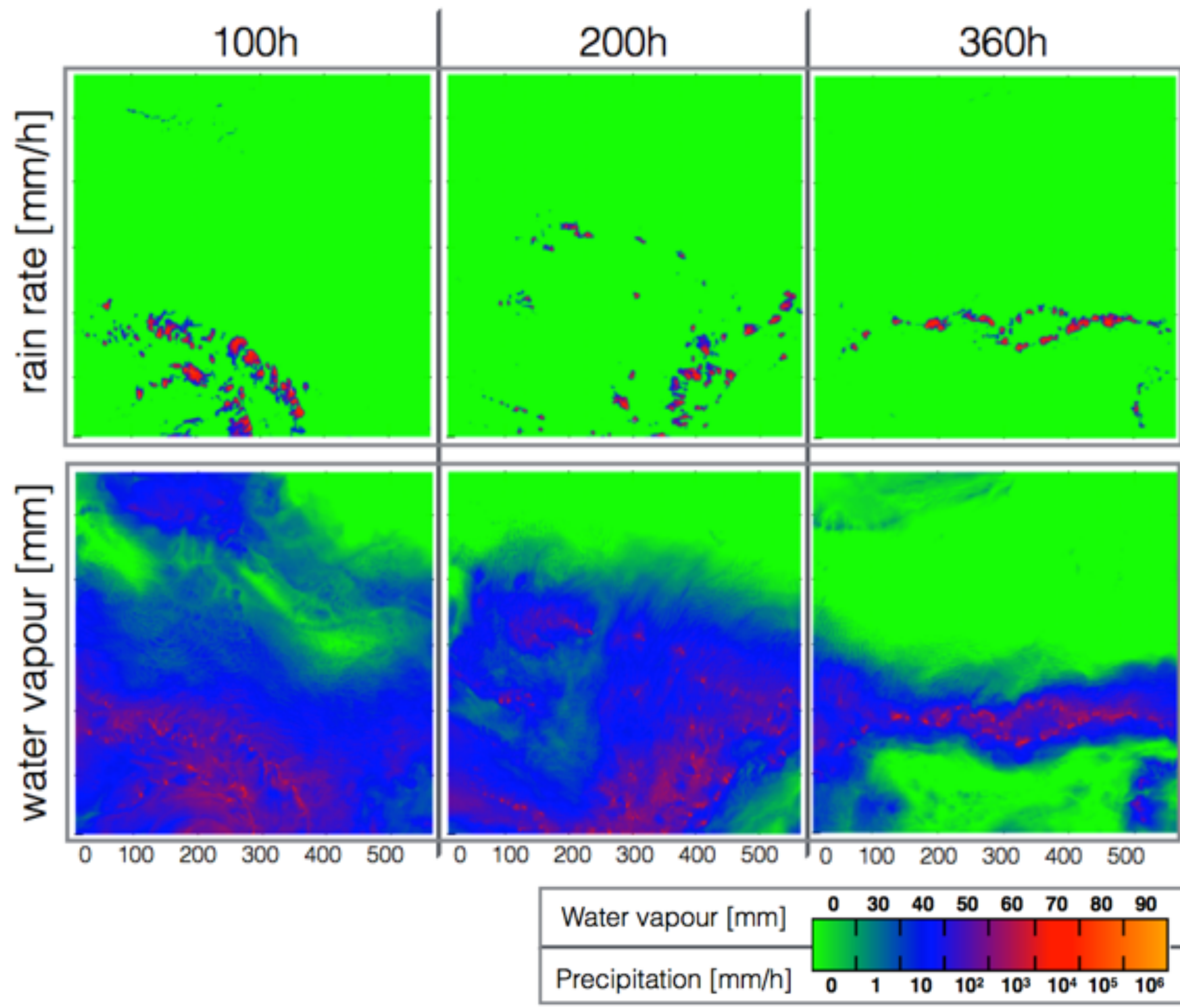
The lateral boundary conditions come from ECMWF operation analyses (updated every 6 h), as in Holloway et al. (2013).

Run B: Realistic case with land

B. Indian Ocean Case

This realistic run starts on the 25-01-2009 and it lasts 15 days. Its domain is 4km griding of 70-80E and 5S-5N. It has some small islands in the north-east section of the domain.

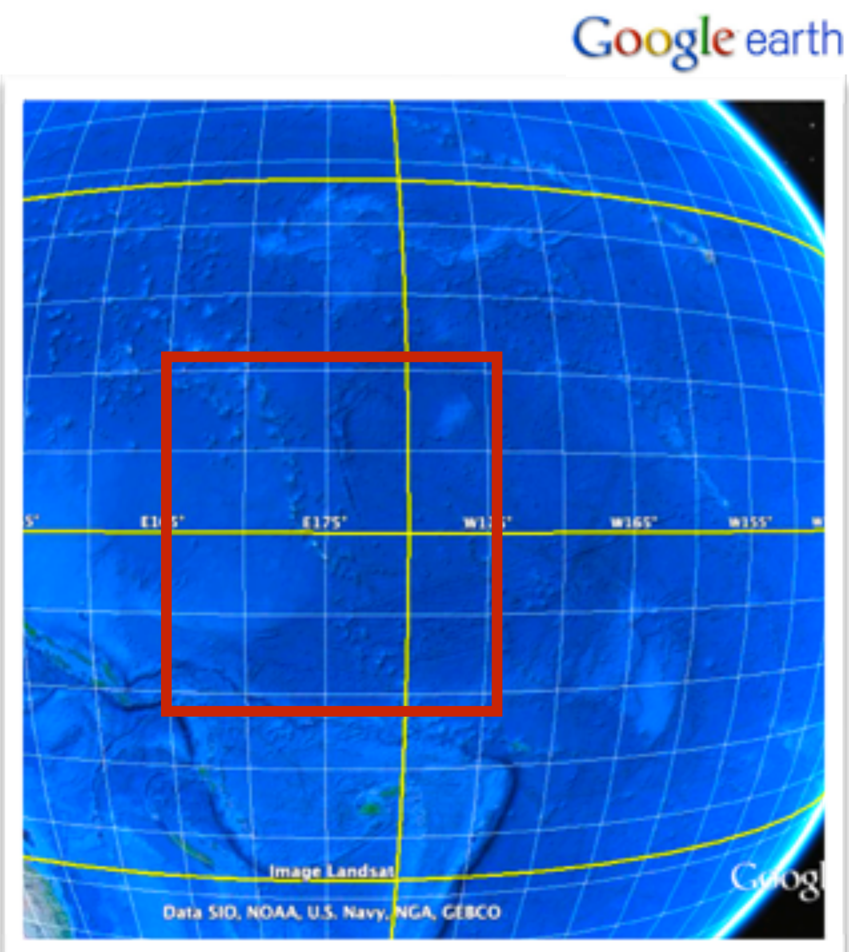


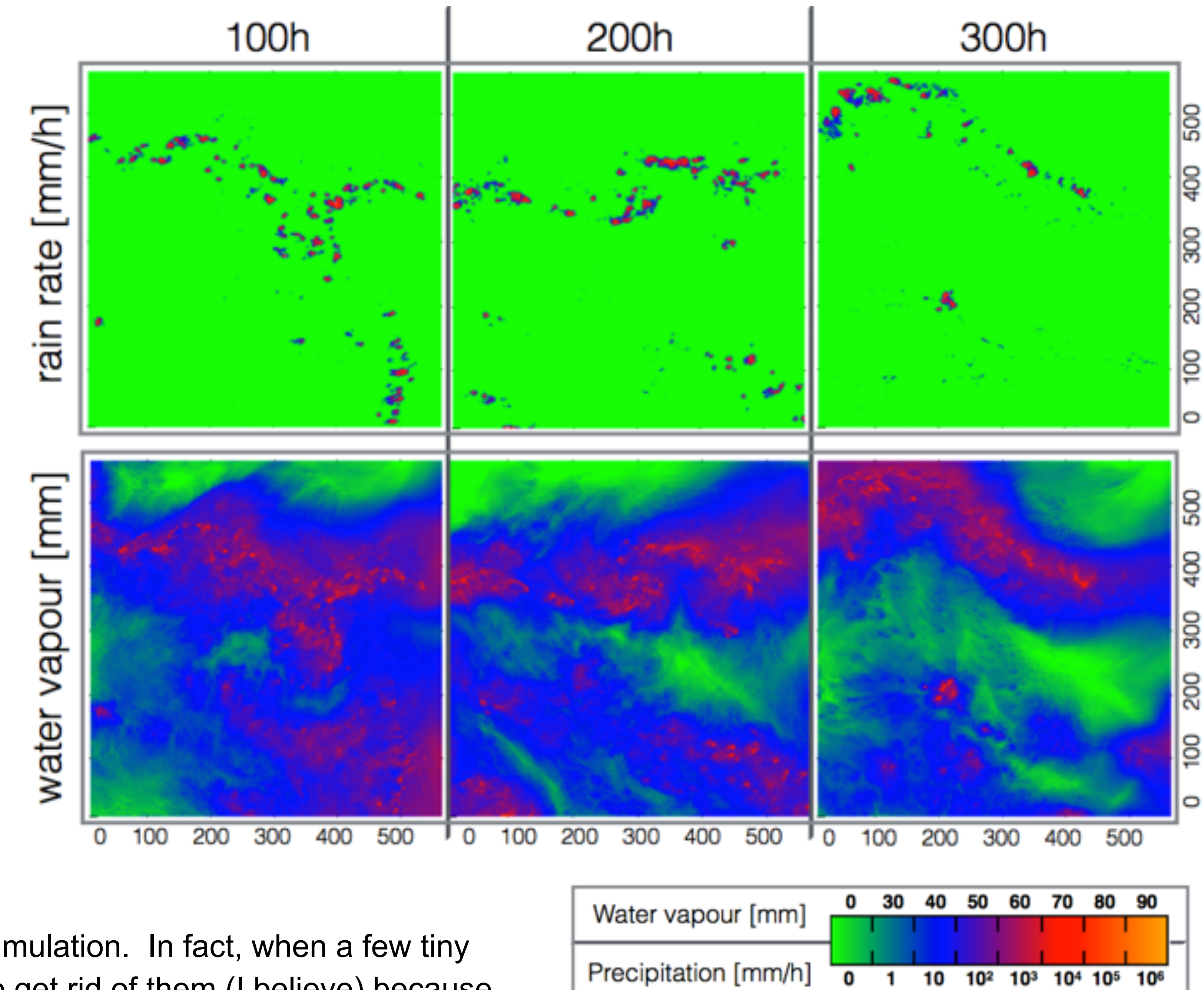


Run C: Realistic run without land

C. West-central Pacific Case

We also data from a realistic simulation a domain in the West Pacific, 10 S - 10 N, 165 E to 185 E, starting on 2009-05-02. It is has ‘no land’ and it is run for 15 days





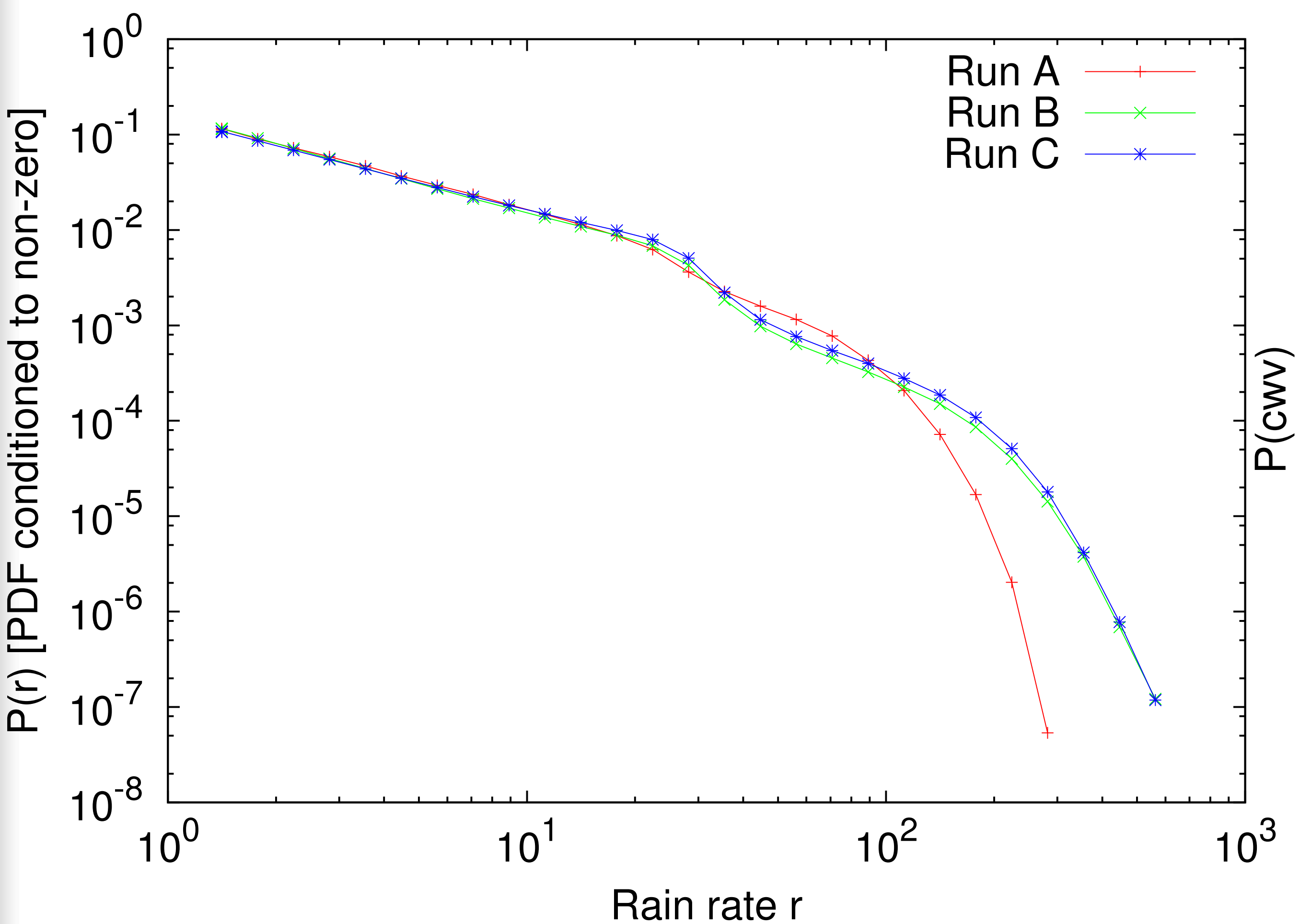
<u>‘no land’</u>

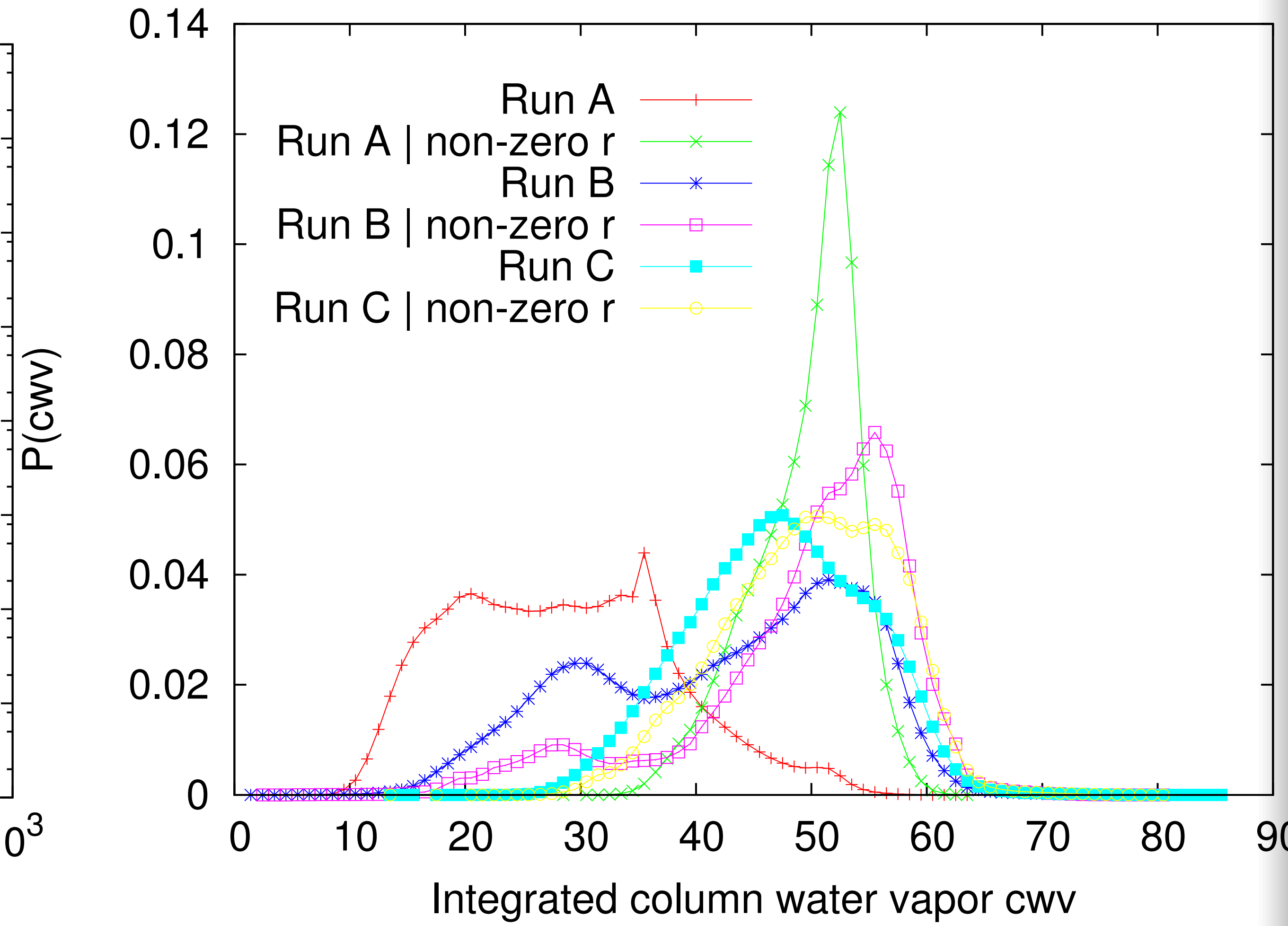
But those tiny islands are not included in the simulation. In fact, when a few tiny islands did appear automatically we decided to get rid of them (I believe) because the ancillary files had no neighboring land areas to pull soil data etc. from.

Rain Rate and water vapour distributions

For rain rate higher than 0.1 mm/h can be approximated with a power law with an exponential tail.

The column water vapour distributions are bimodal.

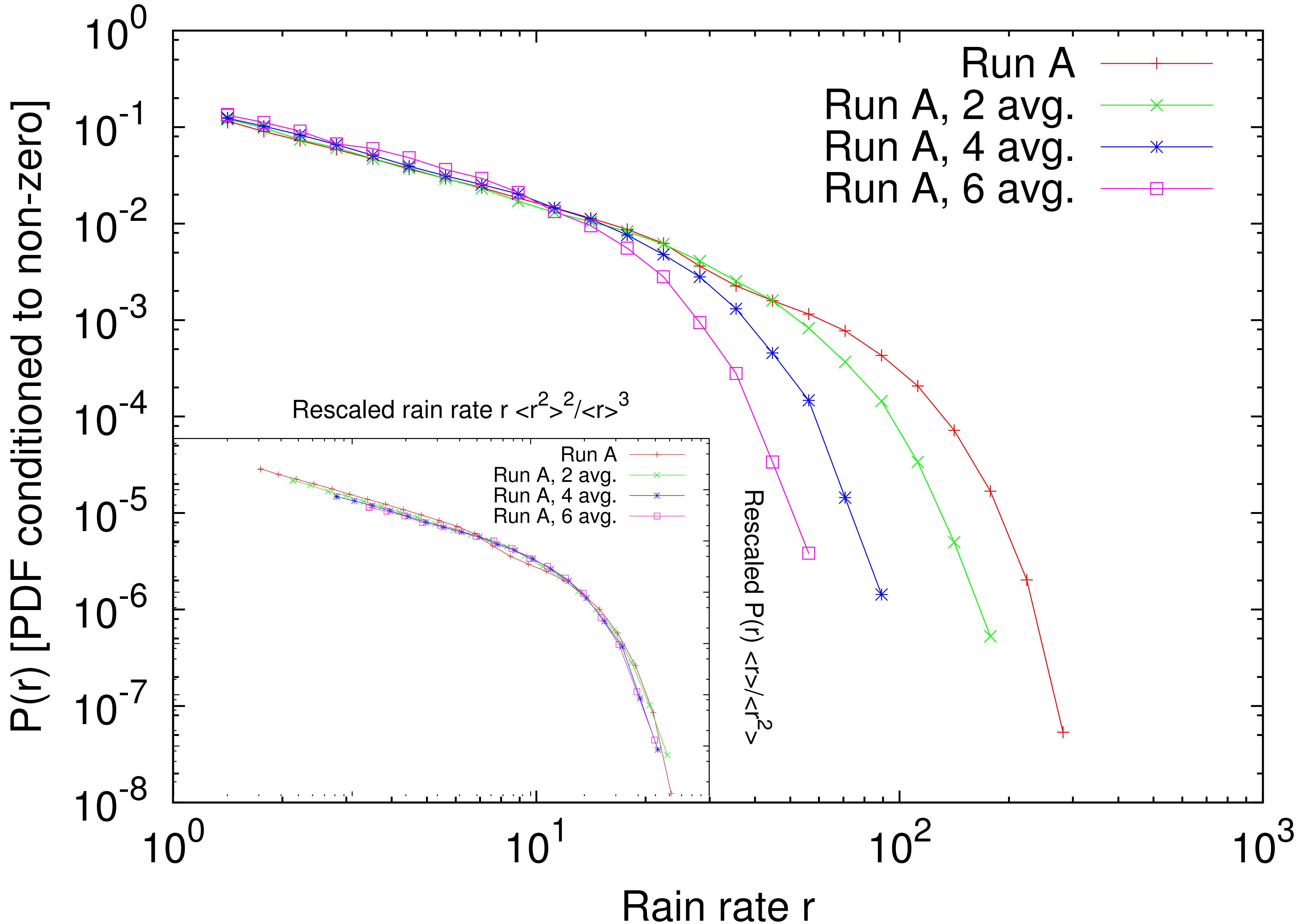




When we conditioned to water vapours when precipitation is non-zero, we observe a maximum before the so-called 'critical value' in Peters and Neelin (2006).

We do not obtain long tails on the CWV distribution.

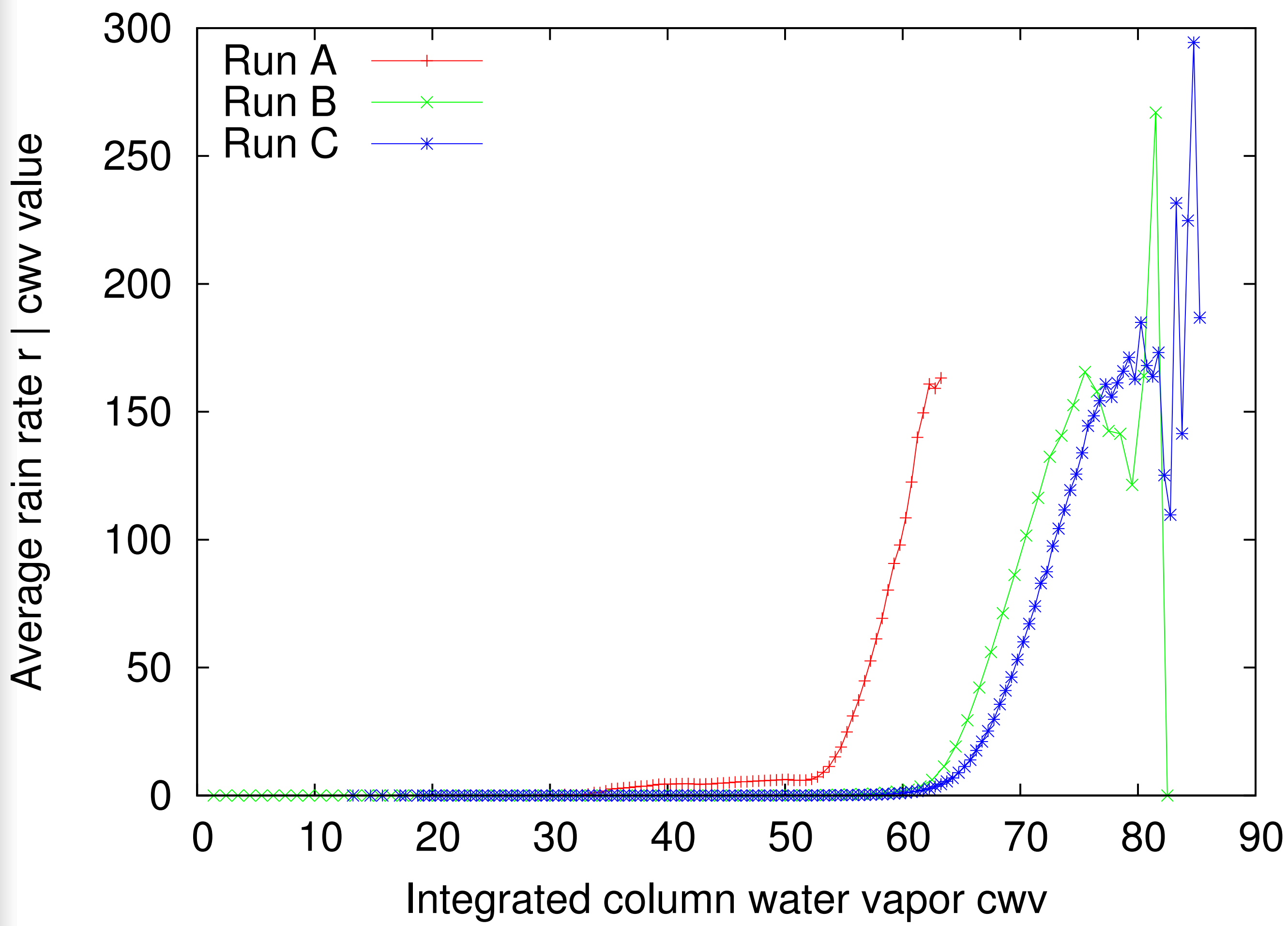
Coarse grained rain rate distributions

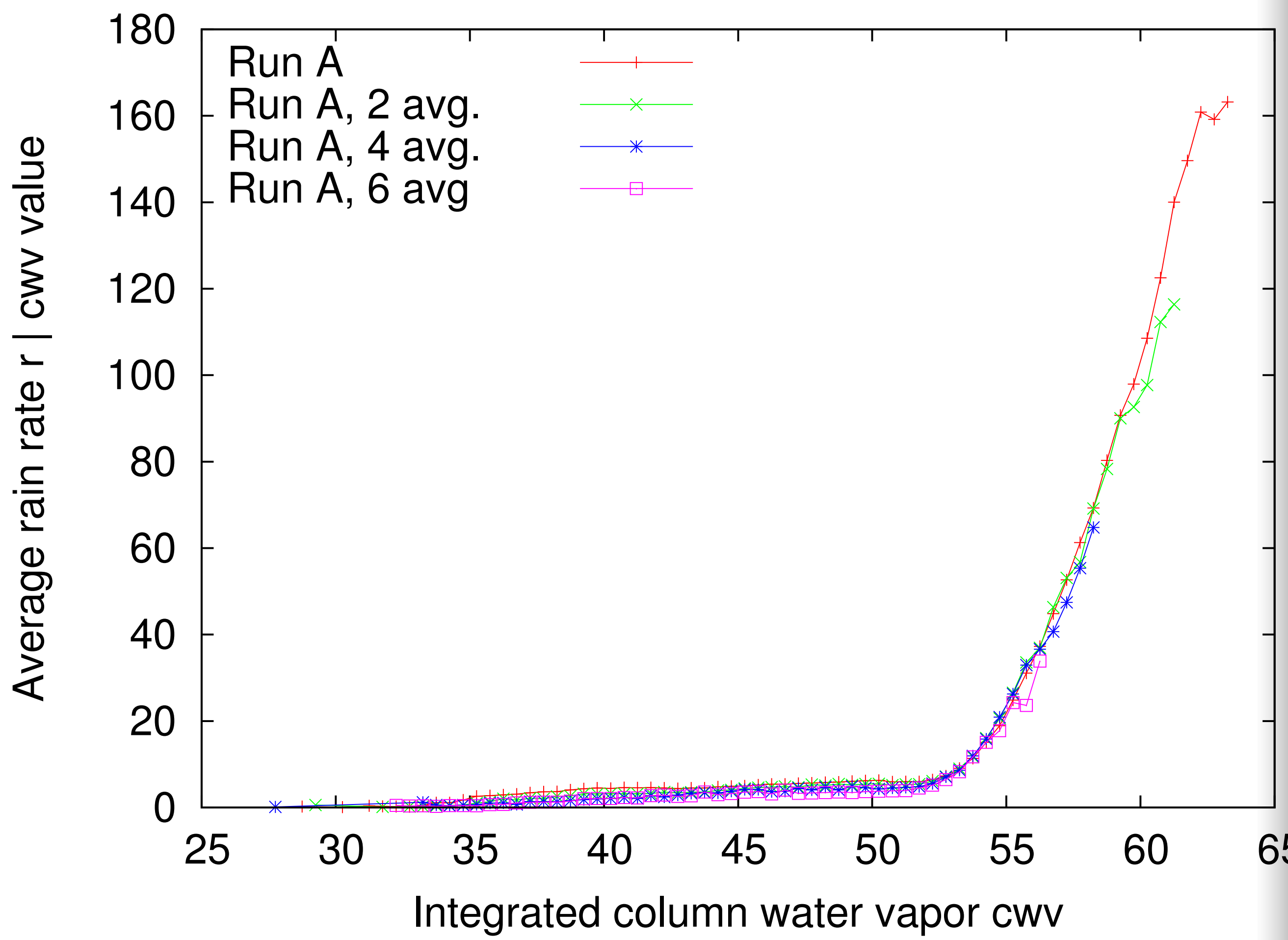


Avg. Precipitation-Moisture Relationship

The idealised run curve picks up much earlier than the realistic runs.

For the idealised run and for the spatially coarse grained corresponding output, the curves are compatible an asymptotic approach to a maximum cwv value.

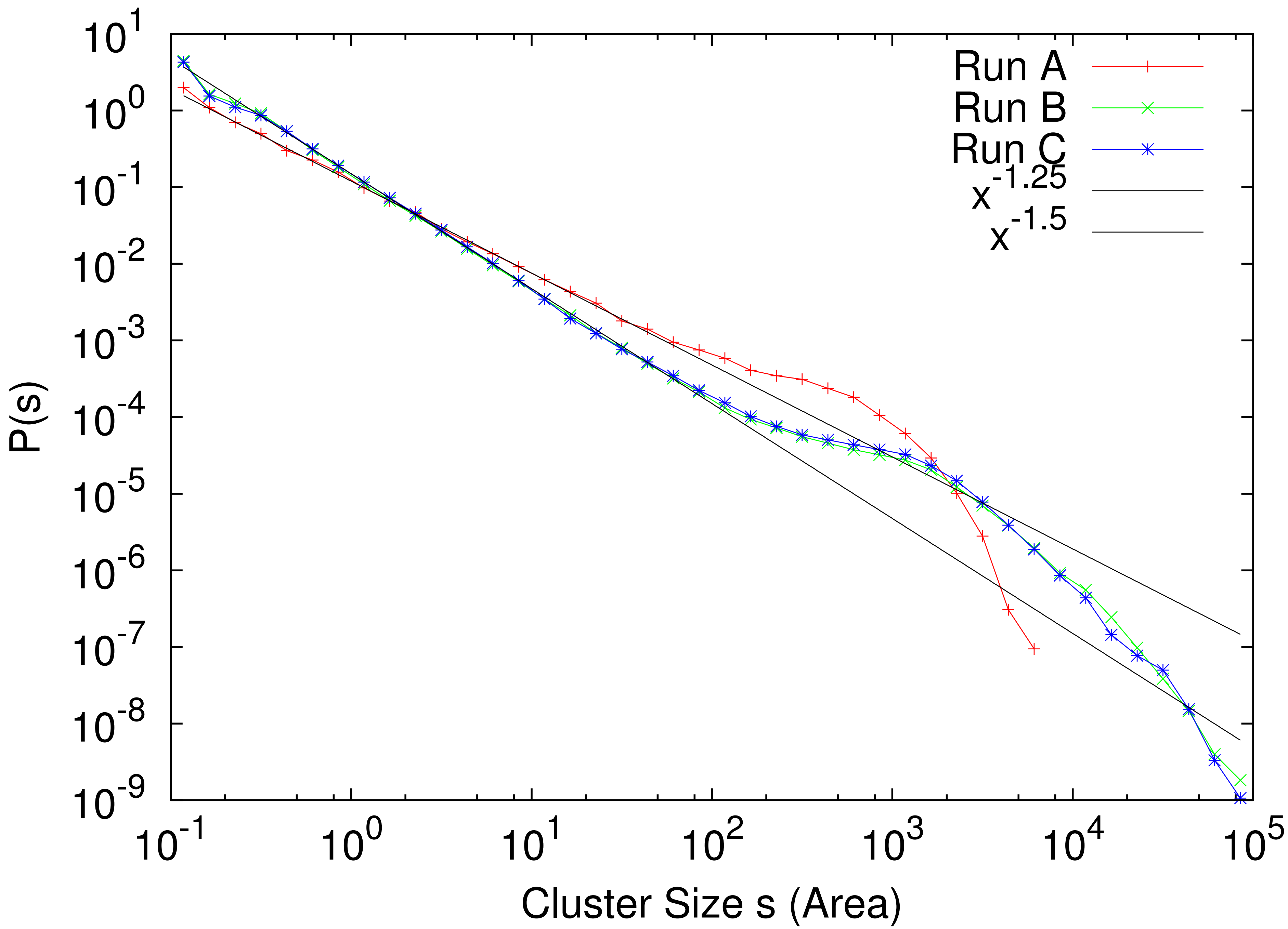




For the realistic runs, it is unclear if it saturates or not around a precipitation average value. However, it seems the fluctuations seem to disappear - it may be a boundary effect.

Cluster Properties

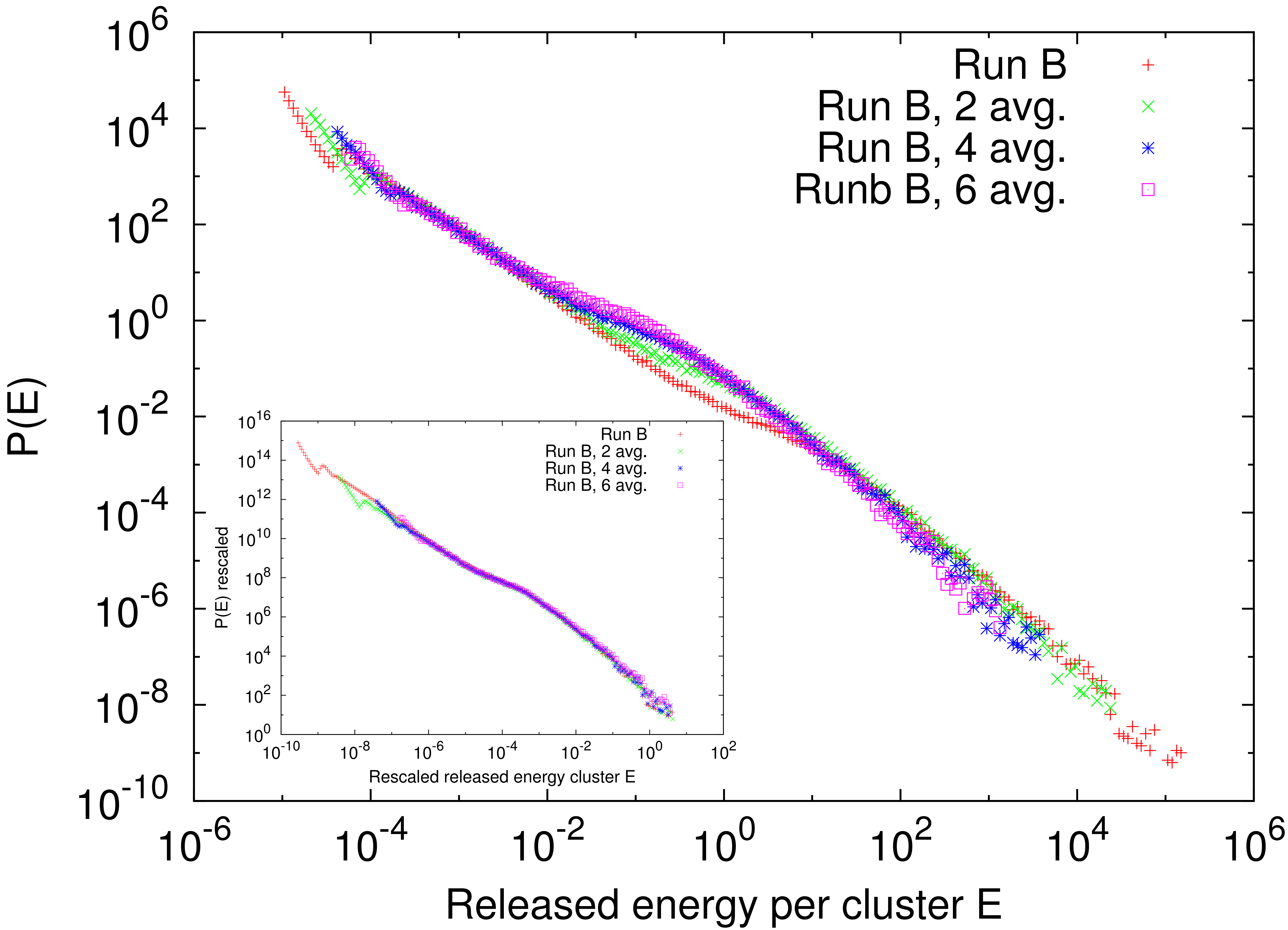
In observations, the distributions can be approximate by a power law for several orders of magnitude (as seen by Peters et al. (2009); Wood and Field (2011)).



Cluster size (horizontal area of the cluster) distribution for the different runs.

‘Energy’ / Cluster Properties

We also look at how cluster statistical properties change with coarse graining.
We consider ‘Energy released’ = area multiplied by the total amount of rain.



Work in progress

- We are working on the analysis with 1 minute temporal resolution (the plots I showed were for hourly data).

- Look at the behaviour of the correlation function for the precipitation field under changes of the background fields of water vapour, temperature, etc. That's tricky thought.

- Explore possible mechanisms by conditioning our analysis to other variables such as vertical velocity.

- Expand our analysis to cold pools (look at clusters of cold temperature).

Well informed physically relevant toy models are the key to further explorer the possible mechanisms.

Others idealised runs

- constradcool constant radiative cooling
- constradcool_aggstart constant radiative cooling and initialised from the last time of the control*
- constradnorainevap constant radiative cooling and no rain evaporation
- constradsurf constant surface fluxes and radiative cooling
- constradsurf_aggstart constant surface fluxes and radiative cooling and initialised from the last time of the control*
- constsurfflux constant prescribed surface fluxes
- constsurfflux_aggstart constant prescribed surface fluxes and initialised from the last time of the control*
- norainevap no rain evaporation
- sst290 colder SST experiments (only 20 days)
- sst295 colder SST experiments (only 20 days)

Conclusions

- The idealised UM in radiative-convective equilibrium reproduces many of the findings of previous work.
- The rain rate distributions can be approximated with a power law with an exponential tail for the three cases.
- The column water vapour distribution picks up around the so-called ‘critical value’ in Peters and Neelin (2006), but we do not observe long tails.
- The functional relationship between column water vapour and the average precipitation has a clear pick up.
- The effect of spatial averaging does not explain the differences, as suggested by Yano et al. (2012). This relationship study is ill-posed due to its big sensitivity to noises.
- The distribution of cluster sizes are present clear differences for the idealised and the realistic runs.
- The energy released per cluster distribution present scaling properties.

Some references

- Holloway, C. E., and S. J. Woolnough, 2016. J. Adv. Model. Earth Syst., in press.
- Stein, T. H. M., D. J. Parker, R. J. Hogan, C. E. Birch, C. E. Holloway, G. M. S. Lister, J. H. Marsham, and S. J. Woolnough, 2015. Q. J. Roy. Meteorol. Soc., 141, 3312-3324.
- Ahmed, F. and Schumacher, C. (2015). J. Geophys. Res.
- Gilmore, J. B. (2015). J. Atmos. Sci., 72:2041–2054.
- Holloway, C. E., Woolnough, S. J., and Lister, G. M. (2013). J. Atmos. Sci., 70(5): 1342–1369.
- Hoshen, J. and Kopelman, R. (1976). Phys. Rev. B, 14(8):3438.
- Peters, O. and Neelin, J. D. (2006). Nature Phys., 2:393–396.
- Peters, O., Neelin, J. D., and Nesbitt, S. W. (2009). J. Atmos.Sci., 66(9):2913–2924.
- Wood, R. and Field, P. R. (2011). J. Clim., 24(18):4800–4816.
- Yano, J.-I., Liu, C., and Moncrieff, M. W. (2012). Sci., 69(12):3449–3462.

Thanks!

Acknowledgments

Data

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Travel Funding & Hosting

And … thanks to

Alvaro Corral, Ole Peters, David Neelin,
Pere Puig and Nicholas Moloney.

Extra Slides - more details about MetOffice UM

PRIMITIVE EQUATIONS

In spherical polar coordinates:

Momentum Equation

Continuity Equation

Thermodynamics Equation

Equation of State

Exner function (pressure)

Representation of moisture

Horizontal momentum components

$$\frac{Du}{Dt} = -\frac{uw}{r} - 2\Omega w\cos\phi + \frac{uv\tan\phi}{r} + 2\Omega v\sin\phi - \frac{c_{pd}\theta_v}{r\cos\phi}\frac{\partial\Pi}{\partial\lambda} + S^u,$$

$$\frac{Dv}{Dt} = -\frac{vw}{r} \qquad - \frac{u^2\tan\phi}{r} - 2\Omega u\sin\phi - \frac{c_{pd}\theta_v}{r}\frac{\partial\Pi}{\partial\phi} + S^v,$$

where

$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + \frac{u}{r\cos\phi}\frac{\partial}{\partial\lambda} + \frac{v}{r}\frac{\partial}{\partial\phi} + w\frac{\partial}{\partial r},$$

$$\Pi = \left(\frac{p}{p_0}\right)^{\frac{R_d}{c_{pd}}}, \qquad \text{[Exner function; } p_0 = 1000hPa]$$

$$\theta_v = \frac{T}{\Pi}\left(\frac{1+\frac{1}{\epsilon}m_v}{1+m_v+m_{cl}+m_{cf}}\right). \quad \text{[Virtual potential temperature; } \epsilon = \frac{R_d}{R_v} \cong 0.622]$$

Vertical momentum component

$$\frac{Dw}{Dt} = \frac{(u^2+v^2)}{r} + 2\Omega u\cos\phi \; - \; g \; - c_{pd}\theta_v\frac{\partial\Pi}{\partial r} + S^w.$$

Continuity

$$\frac{D}{Dt}\left(\rho_y r^2\cos\phi\right) + \rho_y r^2\cos\phi\left(\frac{\partial}{\partial\lambda}\left[\frac{u}{r\cos\phi}\right] + \frac{\partial}{\partial\phi}\left[\frac{v}{r}\right] + \frac{\partial w}{\partial r}\right) = 0,$$

where

$$\rho = \rho_y\left(1+m_v+m_{cl}+m_{cf}\right).$$

Thermodynamics

$$\frac{D\theta}{Dt} = S^\theta = \left(\frac{\theta}{T}\right)\frac{\dot{Q}}{c_{pd}},$$

where

$$\theta = \frac{T}{\Pi} = T\left(\frac{p_0}{p}\right)^{\frac{R_d}{c_{pd}}}. \quad \text{[Potential temperature; } \quad p_0 = 1000hPa]$$

State

$$\Pi^{\frac{\kappa_d-1}{\kappa_d}}\rho\theta_v = \frac{p_0}{\kappa_d c_{pd}}. \qquad [\kappa_d \equiv \frac{R_d}{c_{pd}}]$$

Moisture

$$\frac{Dm_v}{Dt} = S^{m_v},$$

$$\frac{Dm_{cl}}{Dt} = S^{m_{cl}},$$

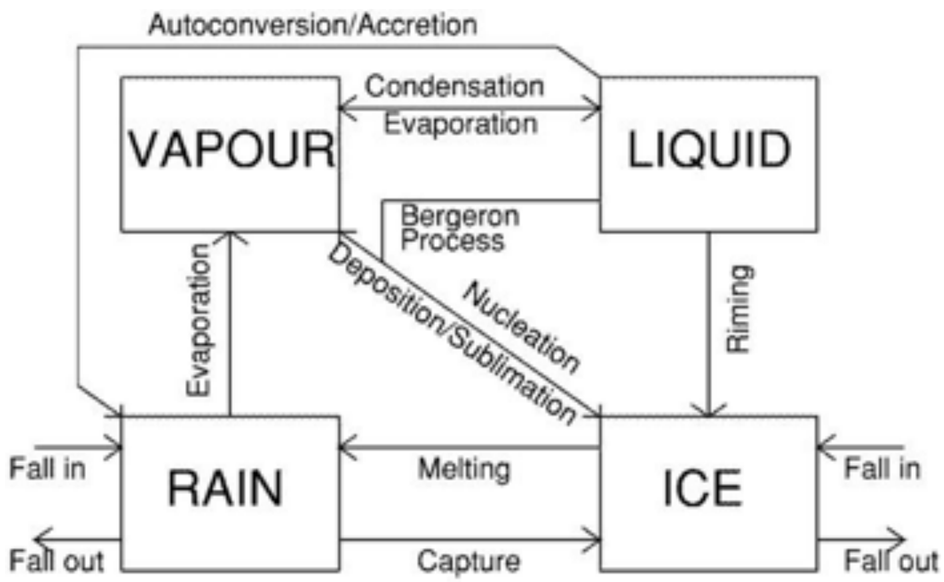
$$\frac{Dm_{cf}}{Dt} = S^{m_{cf}}.$$

plus changed to model coordinates,

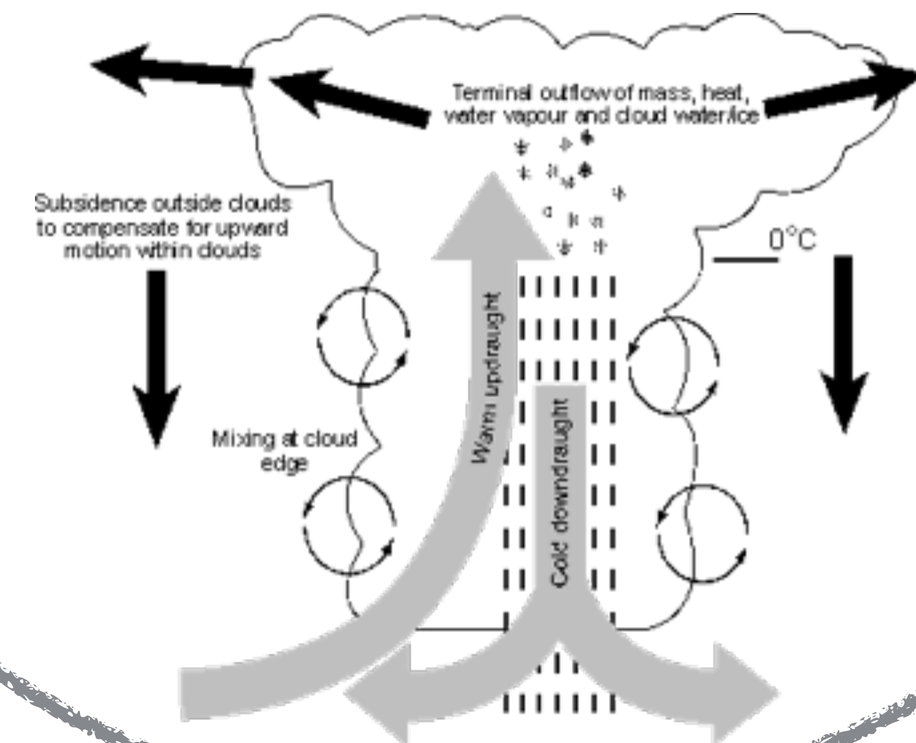
discretised and filtered

Parametrized processes

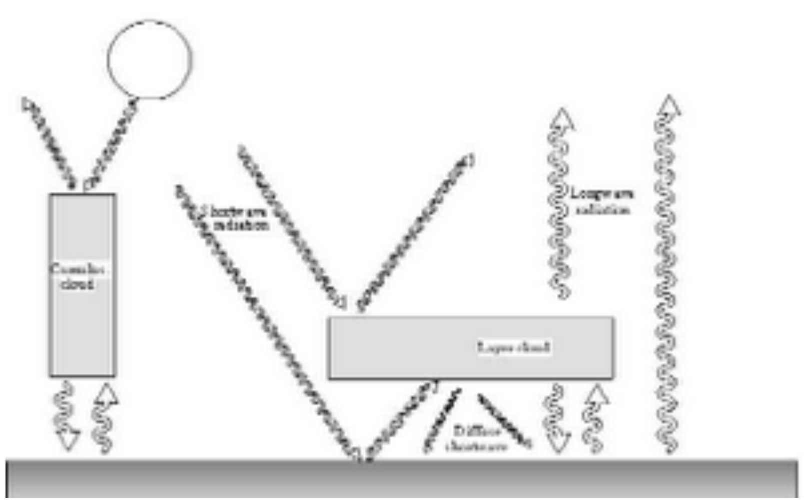
Layer Cloud and Precipitation



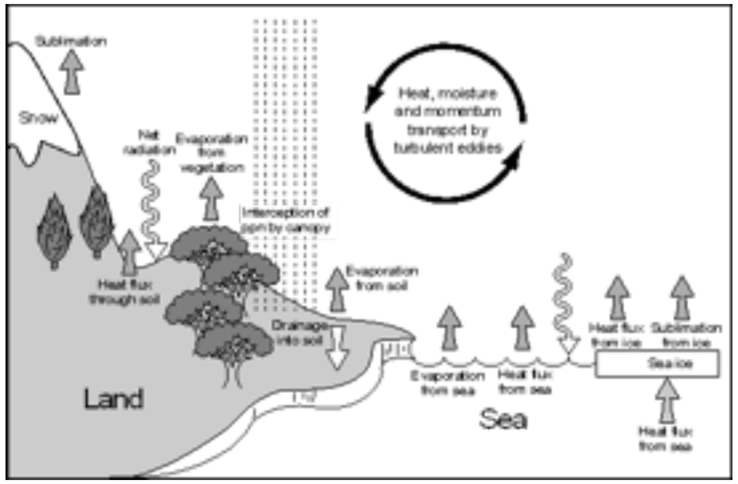
Convective cloud and precipitation



Radiative processes



Surface Processes



Gravity waves