Self-organized criticality in tropical convection?

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With thanks to: Tom Jordan, Chris Holloway, Jun-Ichi Yano, Ole Peters

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Outline

- Traditional picture of tropical convection
- What is self-organized criticality?
- Evidence for SOC in convection
- 1st attempt at SOC model of convection
- No conclusions, just open questions

Traditional picture of tropical convection

The cumulus ensemble

The Arakawa and Schubert (1974) picture

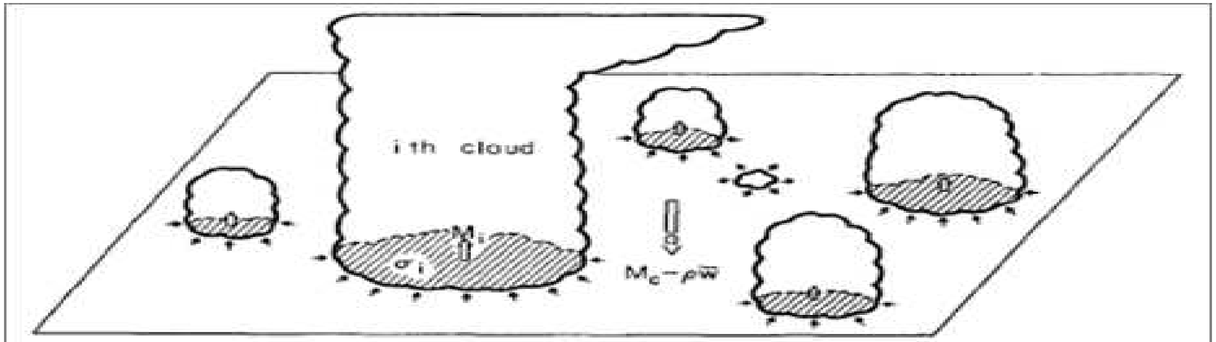


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

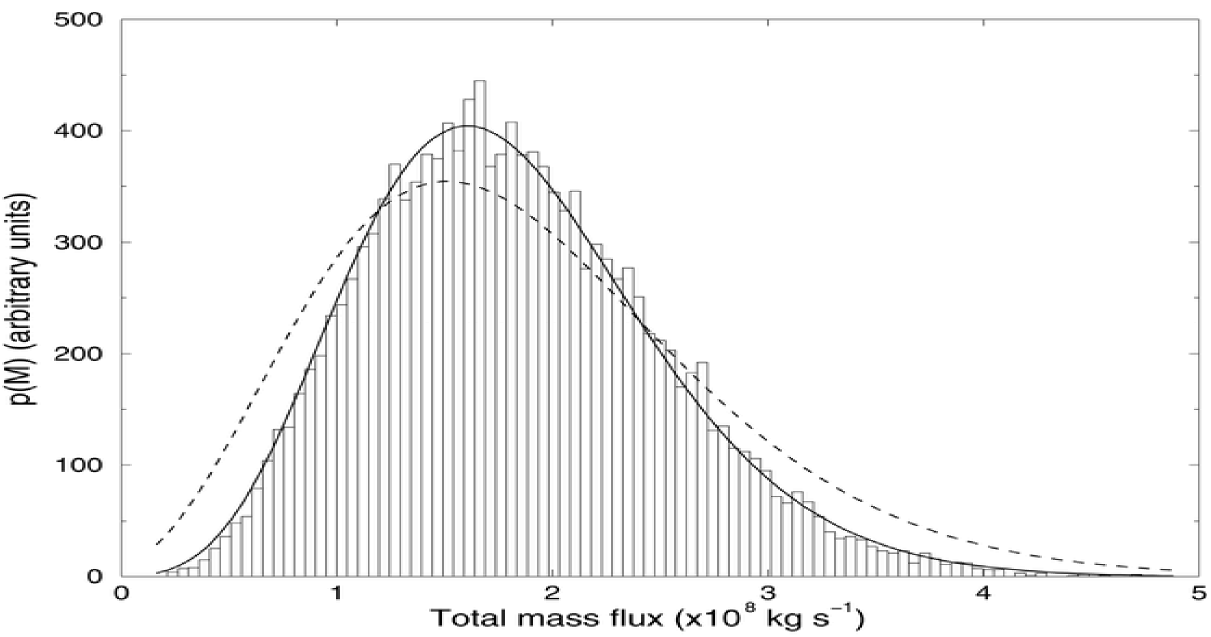
- Convection characterised by ensemble of many cumulus clouds
- Scale separation in both space and time between cloud-scale and the “large-scale”

Large-Scale State

- A region containing many cumulus elements over which the forcing is toleraby uniform
- i.e., a macroscopic state (cf. thermodynamic limit)
- Basis for many convective parameterizations, with grid-box identified with large-scale state
- In statistical equilibrium, properties of the cumulus ensemble are a function of the large-scale state (as in gas kinetics)

For example...

- Can predict pdf of mass flux (or rainfall) in a finite-sized region, assuming (say) that the microscopic components are non-interacting (Cohen and Craig 2006, Davoudi et al 2009)



- Traditional picture stresses statistical equilibrium and no or weak cloud-cloud interactions

What is self-organized criticality?

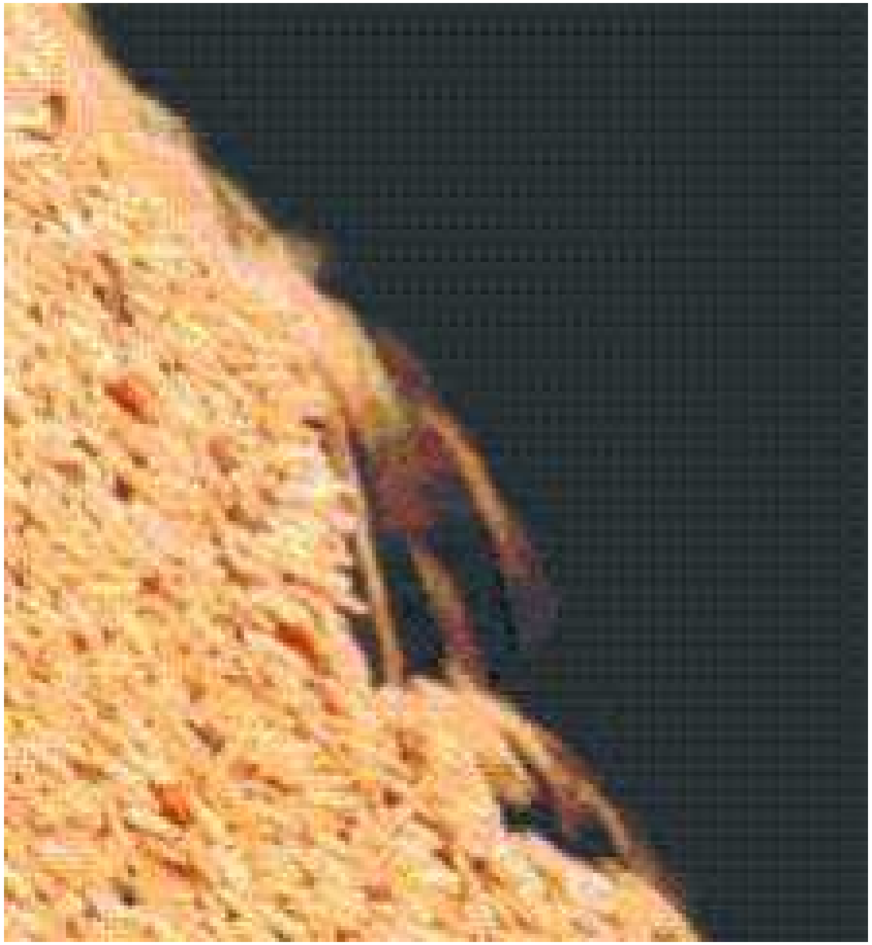
SOC characteristics

- Dynamical system of many dof's whose self-interactions tend to organize the system towards a macroscopic state analogous to an equilibrium system at a critical point
- Key features:
  - A slow, external driving of the system
  - A threshold for the dynamics of individual dof's
  - Interactions between the dof's once the threshold is crossed
  - Fast internal relaxation once the threshold is crossed

SOC expectations

- Expect to find signals of scale invariance:
  - power laws just above the critical point
  - $1/f$ behaviour in power spectra
  - Exponents should be insensitive to any “tuning” of (say) driving process or interaction characteristics
- For a power spectrum $S(f) \sim f^{-\alpha}$ then auto-correlation function $\sim t^{\alpha-1}$
- So very long-range correlations for $\alpha \approx 1$
- No characteristic space or timescale in the system

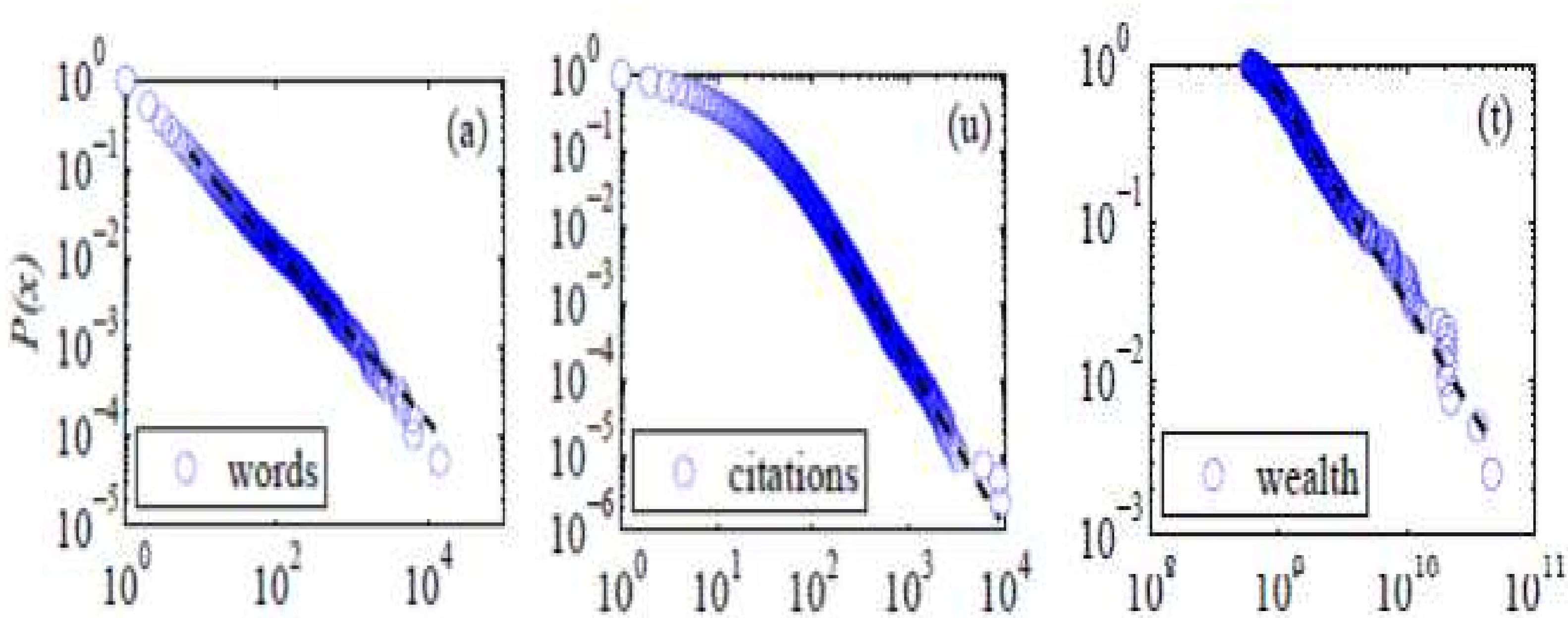
SOC in practice



- Has provided useful insights for ricepiles, earthquakes, forest fires, raindrops rolling down a window...

Health warning

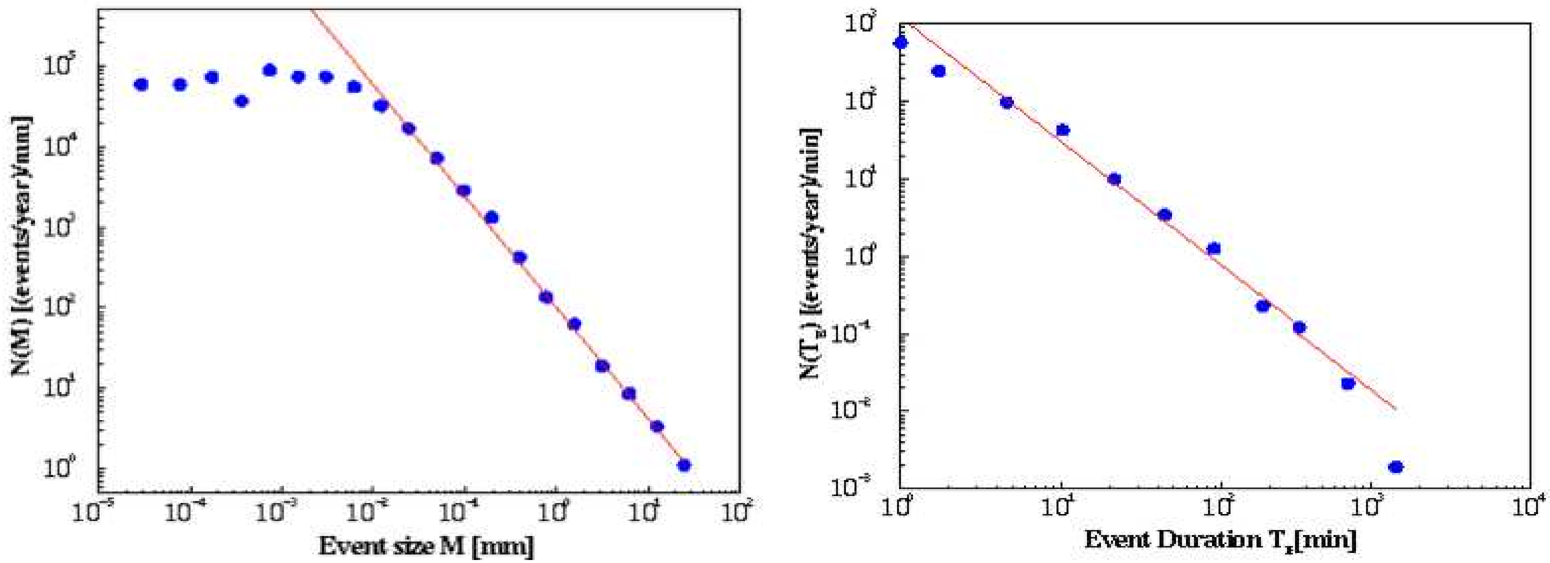
- Some systems labelled as SOC are probably not
- Least-squares regression on a log-log plot can be highly misleading! (Clauset et al 2009)



Evidence for SOC in convection

Scale invariance

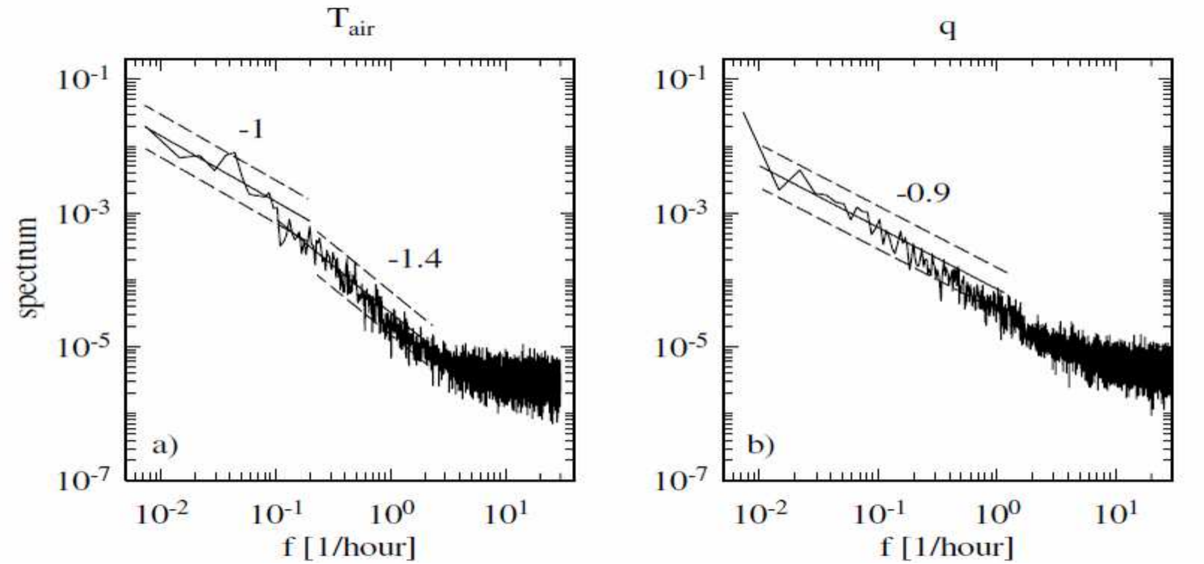
Peters and Christensen (2002): radar rainfall data over Germany



- Rainfall from an event, and event duration show power laws over 3 orders of magnitude

$1/f$ behaviour in tropical Pacific

Yano et al 2003: data from 13 stations in TOGA-COARE



- Long-range correlations in near-surface temperature, moisture and wind speed

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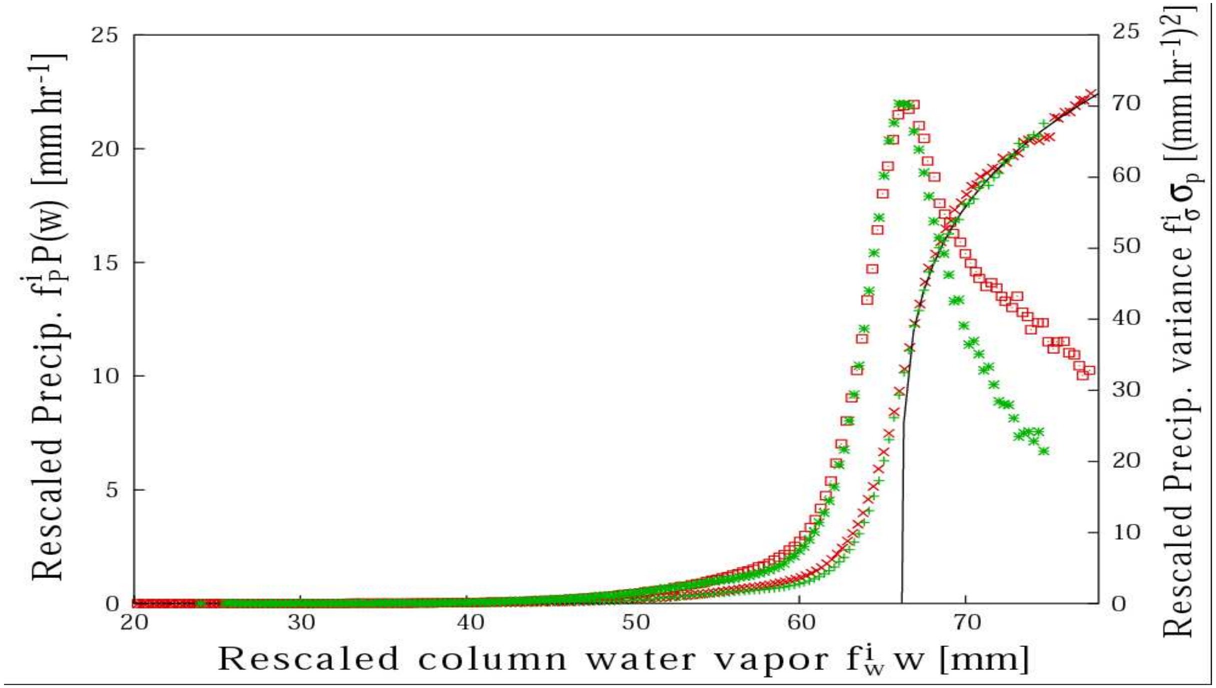
Critical point

Peters and Neelin 2006: TRMM satellite data for various ocean basins



- Threshold in column water vapour, with power law above and large variance near threshold

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Exploratory attempt at SOC model of convection

What do we need to believe SOC?

1. A physical system with the basic ingredients (slow drive, local thresholds etc)
2. A simple model of the physical system that predicts SOC, with key exponents
3. Robust empirical evidence

Where are we now?

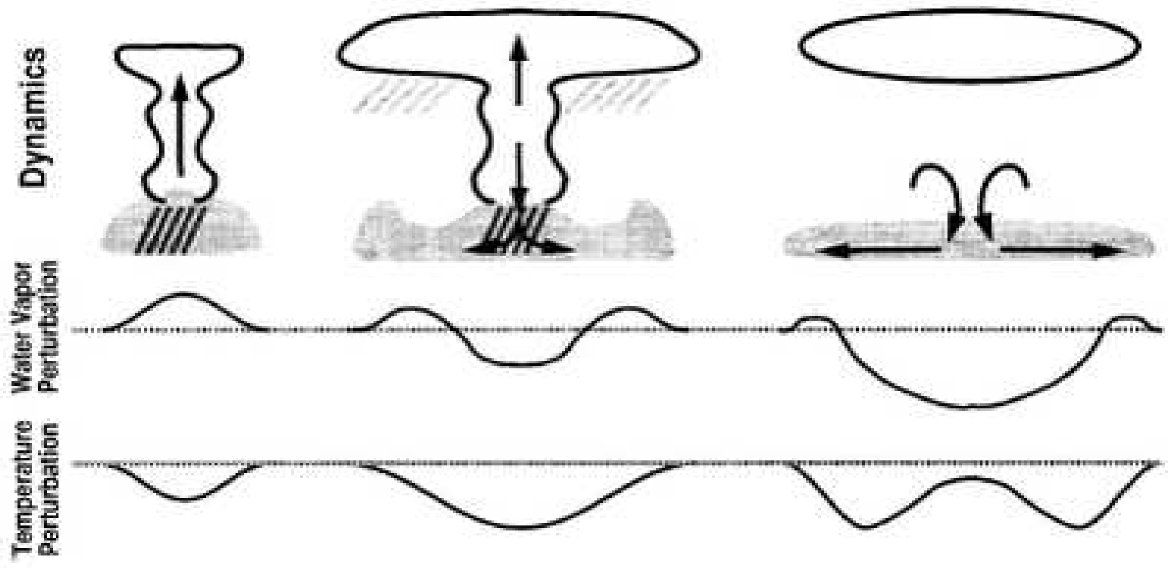
Peters and Neeelin 2006:

> ...these findings beg for a simple model of the atmospheric dynamics responsible...

Muller et al 2009:

> the empirical evidence fror SOC is essentially circumstantial... until a clear physical mechanism is provided...

Possible interaction mechanism



- Cold pool outflow perturbs boundary-layer moist static energy
- Increased chance to activate new convection in neighbourhood of an active cell

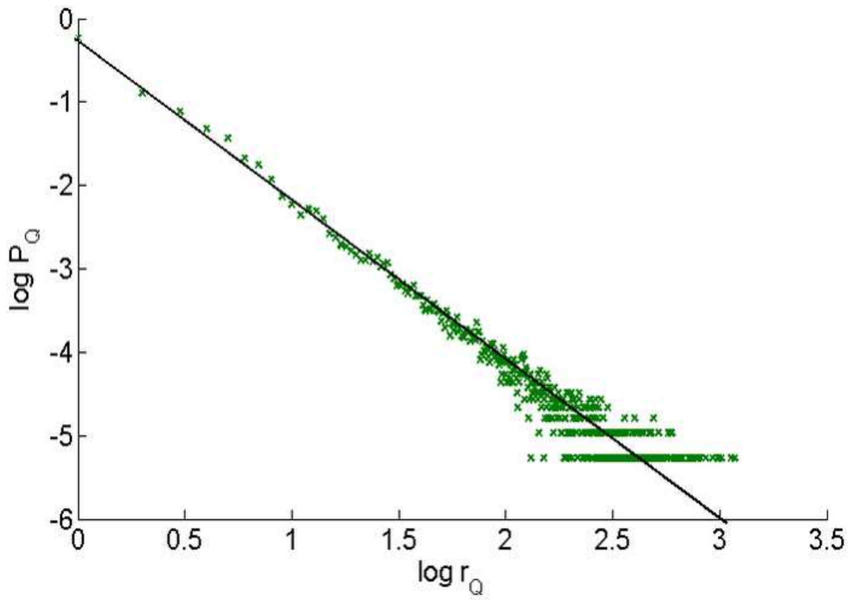
The model algorithm

On a grid of $N \times N$ points, doubly periodic, randomly initialized...

- Apply a small forcing increment everywhere
- If threshold is crossed anywhere then
  - Rapid relaxation event occurs here - reset the point
  - Test if an interaction perturbation can cause a neighbour to pass the threshold
  - If so signal the neighbour(s) to activate at the next step

Limit of small timestep

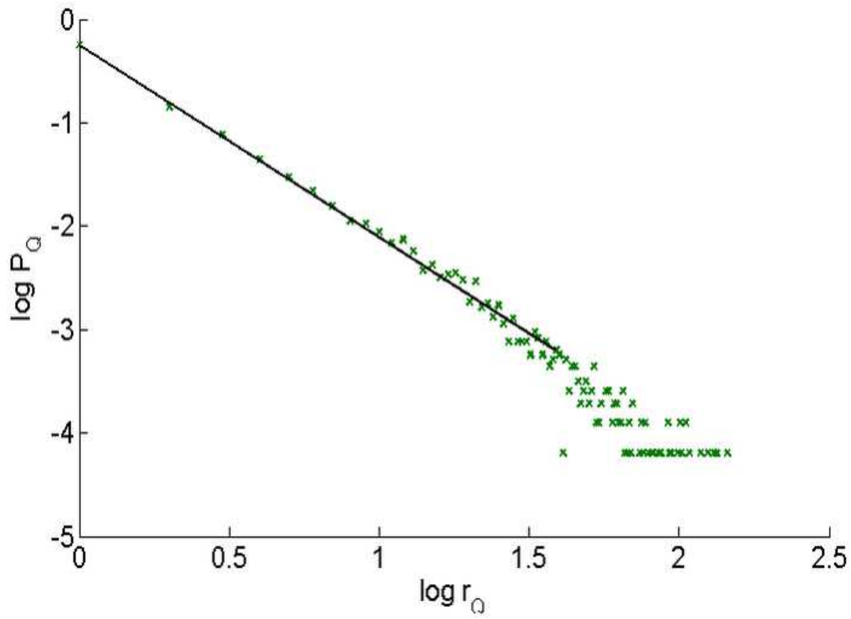
- As $\delta t \to 0$, the model reduces to a textbook SOC system (Sinha-Ray and Jensen 2000)
- Each avalanche that occurs is complete before another event starts



- Storm size distribution for a parameter set close to the SOC limit

For finite timestep

- $\delta t \neq 0$ related to a ratio of timescales: interaction timescale for cold pool perturbation / driving timescale for spontaneous triggering in the absence of interactions



- For a timescale ratio of 10^{-2}
- Power-law like behaviour but over reduced range: breaks down for larger clusters

My own view...

- Tropical oceanic convection has basic features consistent with an SOC system
- Empirical evidence for SOC is strongly suggestive
- SOC stresses role of self-interactions, but what is the key interaction mechanism for convection?
- SOC deals with two timescales, $\tau_{\text{drive}} >> \tau_{\text{relax}}$
- There are two aspects to relaxation, τ_{cloud} and τ_{interact}
- I can believe $\tau_{\text{drive}} >> \tau_{\text{cloud}}$ but how about τ_{interact}??