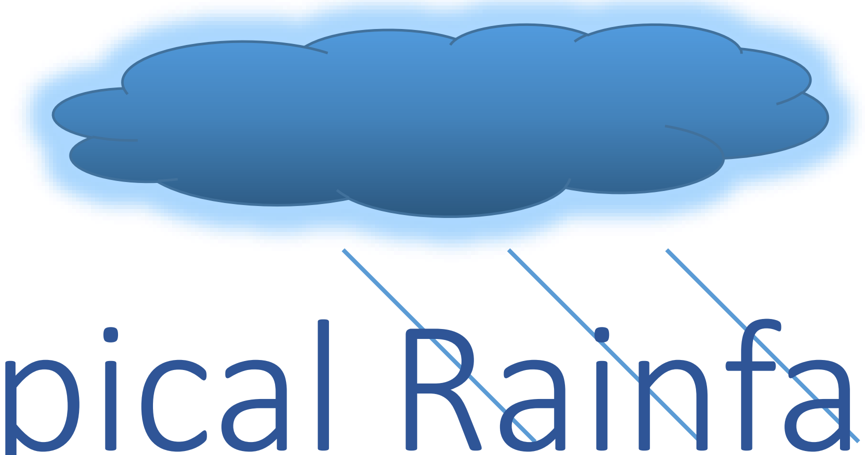


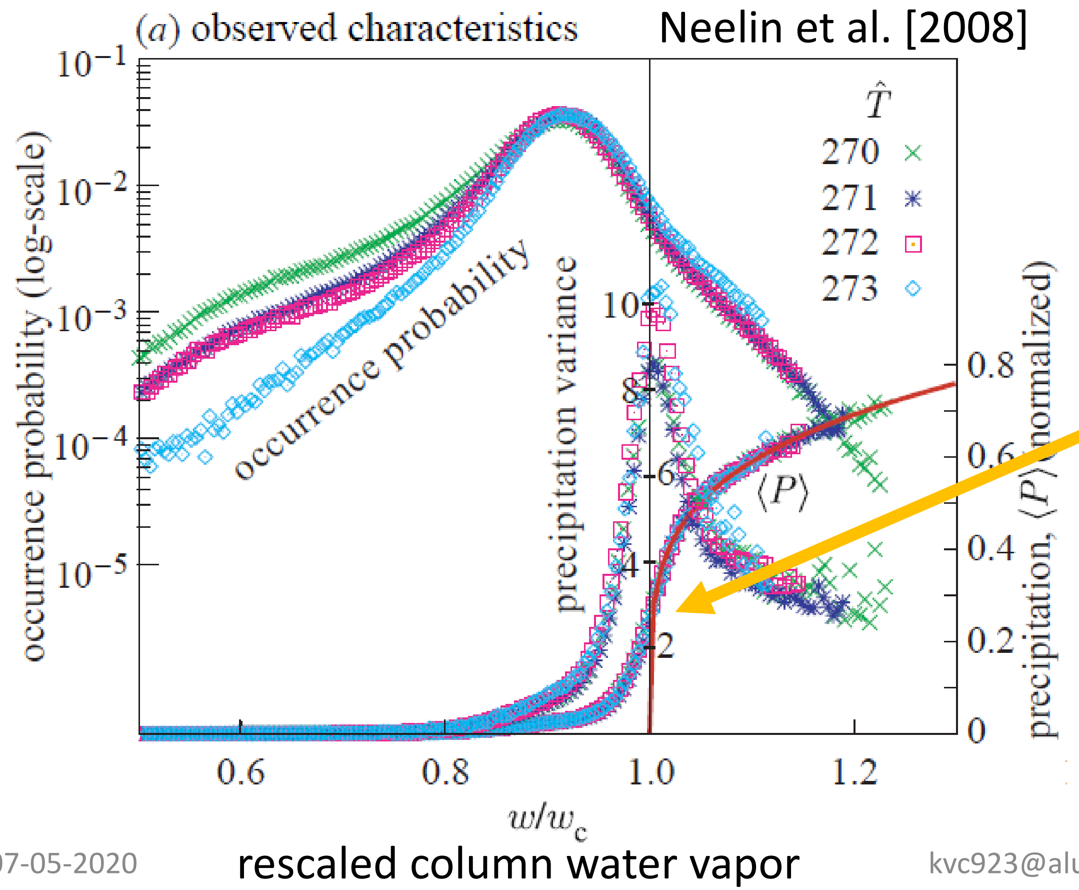
Criticality in Tropical Rainfall: A Simple Water Budget Model

Mikkel Svendsen,
Jan O. Haerter, Bettina Meyer

Atmosperic Complexity,
Niels Bohr Institute, University of Copenhagen

Convection as a critical phenomenon?

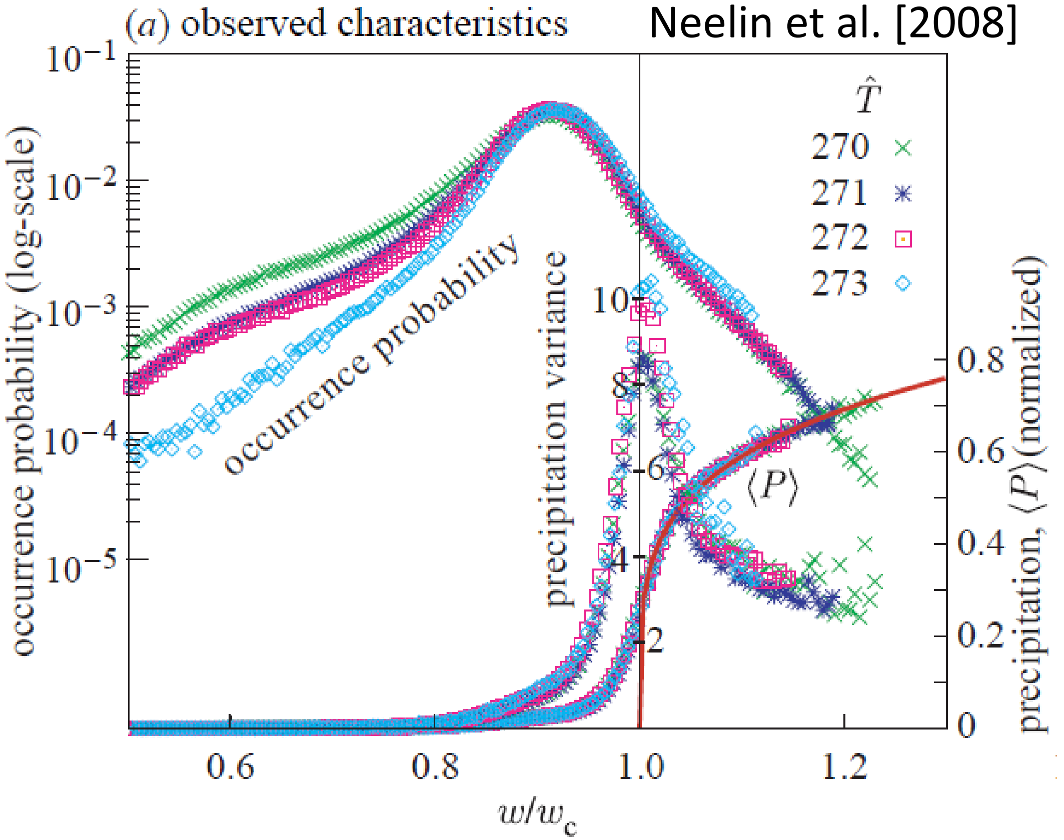
Motivation



Rain rate as a function of column water vapor follows a clear "pickup curve", shifting from essentially zero to sharply increasing, once surpassing a critical moisture value.

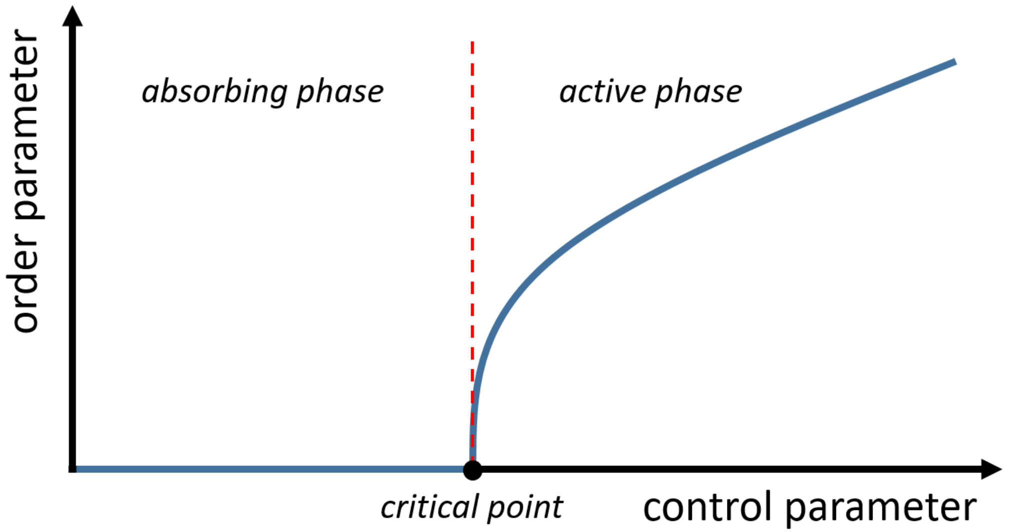
Convection as a critical phenomenon?

Motivation



Neelin et al. [2008]

rescaled column water vapor



This indicates a phase transition, separating a non-raining "inactive" phase from a rainy "active" one.

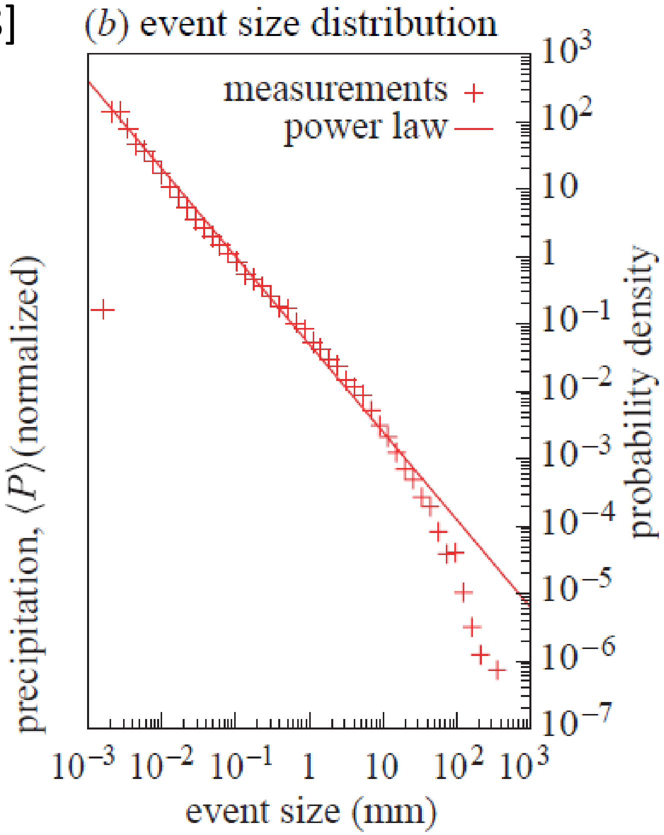
Convection as a critical phenomenon?

Motivation

Neelin et al. [2008]

Rain events and clusters, defined as groups of contiguous rainy points in space and/or time, have size distributions well described by power laws.

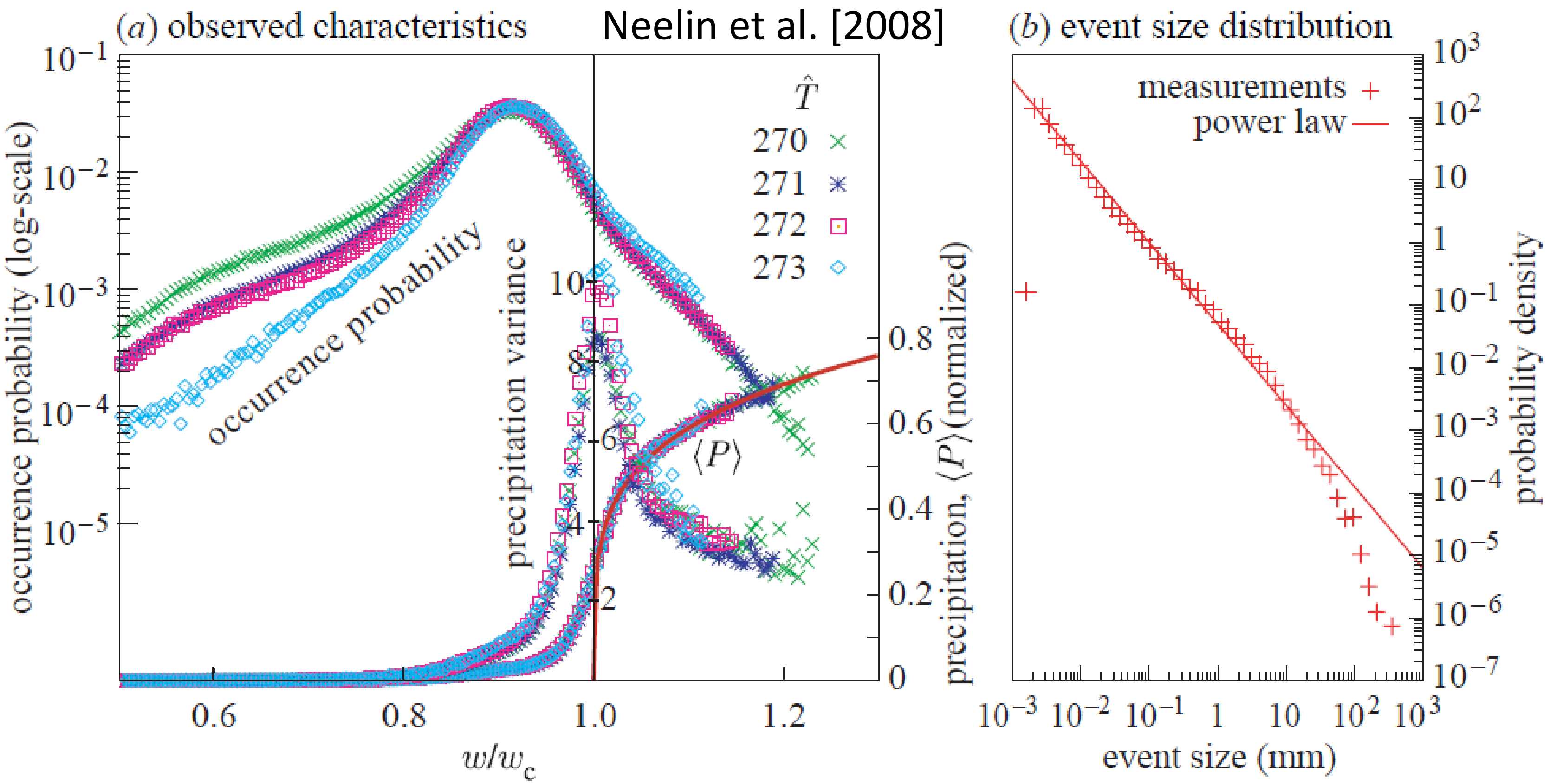
This suggests a proximity to the critical transition point, where "scale-free" power law distributions are expected.



event size = accumulated rainfall from rain start till it stops

Convection as a critical phenomenon?

Motivation



Together this indicate that tropical convection may be an instance of self-organized criticality (SOC)

What is SOC?

Characteristics:

- Criticality: Long-range correlations in space and time, giving scale-free (power law) distributions of integrated quantities
- Self-organization: System tunes itself toward critical point (of continuous phase transition)

Typical causes:

- Slow drive (1D sandpile: Add 1 grain each timestep)
- Fast relaxation above threshold with neighbor interaction
  (1D sandpile: Once a site has 2 grains, it topples, and distribute a grain to each neighbor, starting an avalache of topplings until all sites have at most 1 grain. Grains leave the system at the ends.)

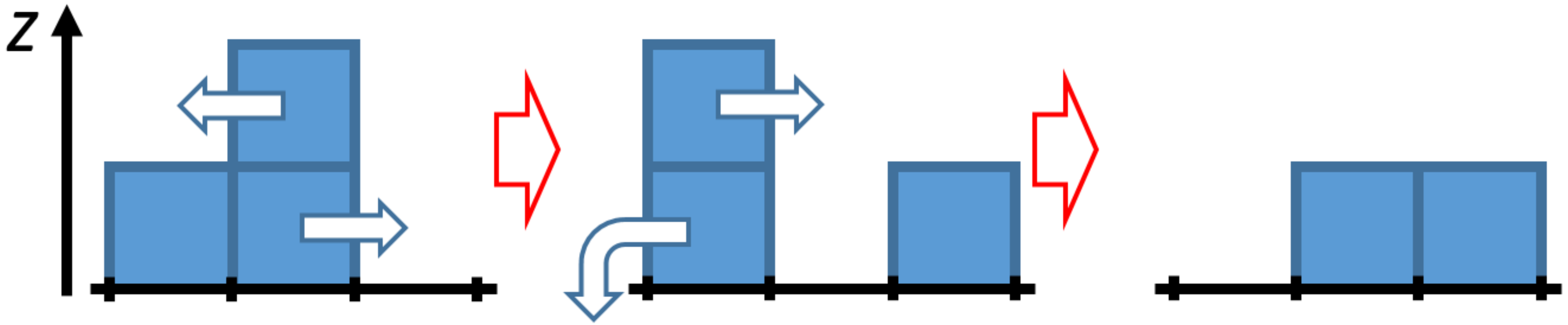
Classic SOC starting point

Sandpile model (1D)

Consider a pile of sand extending along one dimension.
Adding sand at one end will increase the slope.
Once the slope locally passes the maximally stable slope, it topples, stabilizing the local slope, but destabilizing the neigboring slopes.

Thus a single toppling can start an avalanche of succesive topplings, potentially reaching the edge, reducing the overall slope.

1D sandpile avalanche



Formally, let *z(i)* represent the local slope at site *i = 1,...,L*.

Driving Add 1 to a random site *i*: $z(i) \to z(i) + 1$

Activation A site is *unstable* exactly when it reaches a threshold $z^* = 2$

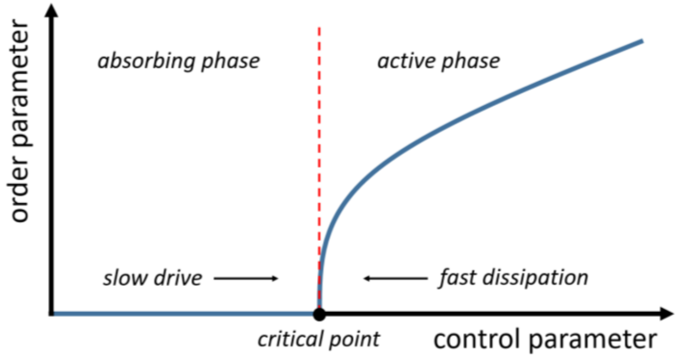
Toppling An unstable site *i* topples by giving 1 to each neighbor:
$z(i) \to 0$,
$z(i-1) \to z(i-1) + 1, \quad z(i+1) \to z(i+1) + 1.$
This toppling procedure continues until all sites are stable

Boundary dissipation If one of the end sites are unstable,
1 leaves the system entirely.

Iterate the whole procedure

The mean slope <z> (control parameter) is tuned to it's critical value by the balance between

- slow addition of grains, and
- loss at boundary due to fast long-range avalanches:



What’s the problem?

If we want to relate idealized **avalanches** to **rain clusters** we get the following issue:

In standard sandpile-like models, activity is spread by waves of toppling having minimal spatial and temporal extend. To observe **spatially and temporally extended clusters** of (rain) activity, active sites must sustain themselves for a longer time than they take to activate their surroundings.

This is obtained by having a deactiviation threshold that is lower than the activation threshold. This enables active sites to stay active for several time steps, helping them connect to active neighbors.

Therefore we introduce...

Changing the rules

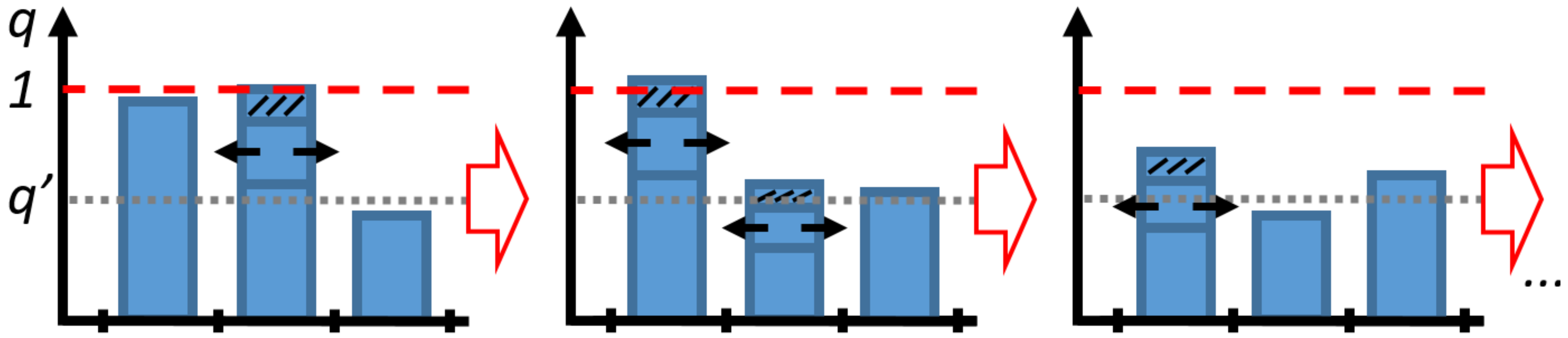
Modified model (2D) – description

Consider the variables column water *q*, convective activity *A* and rain rate *P* on a square lattice.

Activation	Set A=1 wherever $q \geq 1$, and set A=0 wherever $q<q'$. Otherwise keep A.
Bulk dissipation	Fraction *fdiss* of q is removed at active sites: $P=A*fdiss*q$
Toppling	Wherever A=1, redistribute fraction *fdiv* - *fdiss* of q equally to 4 nearest neighbors
Driving	Add input amount E to all sites.

Iterate the whole procedure

modified model



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Iterate the whole procedure

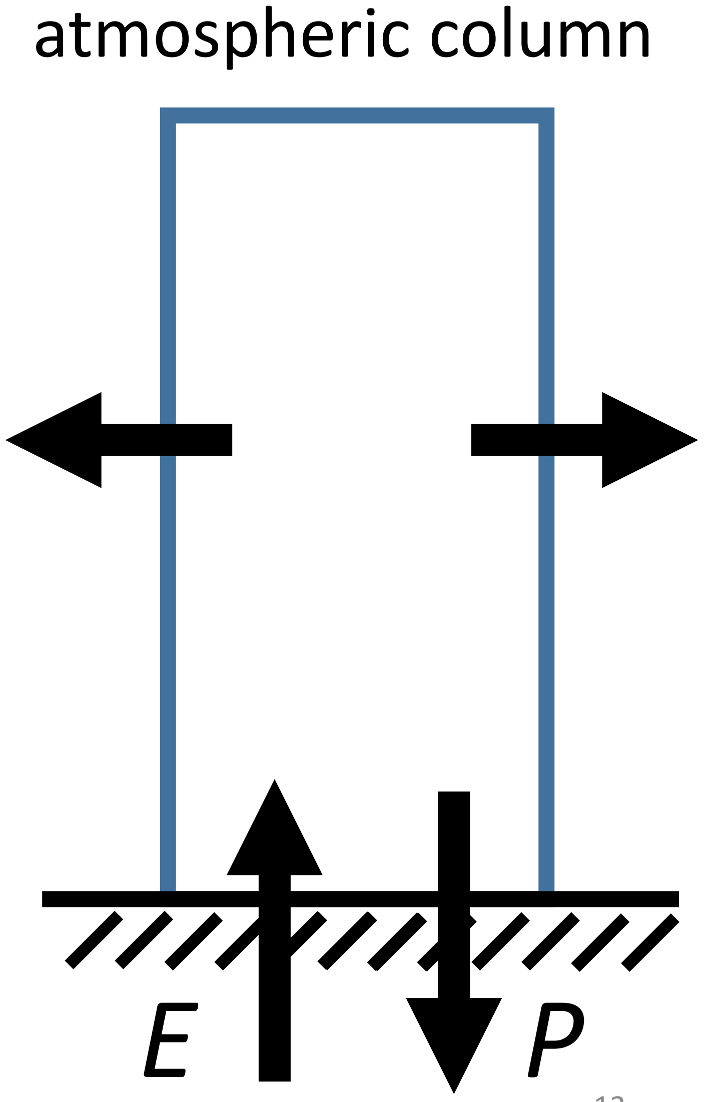
Changing the rules

Modified model – Relation to convection

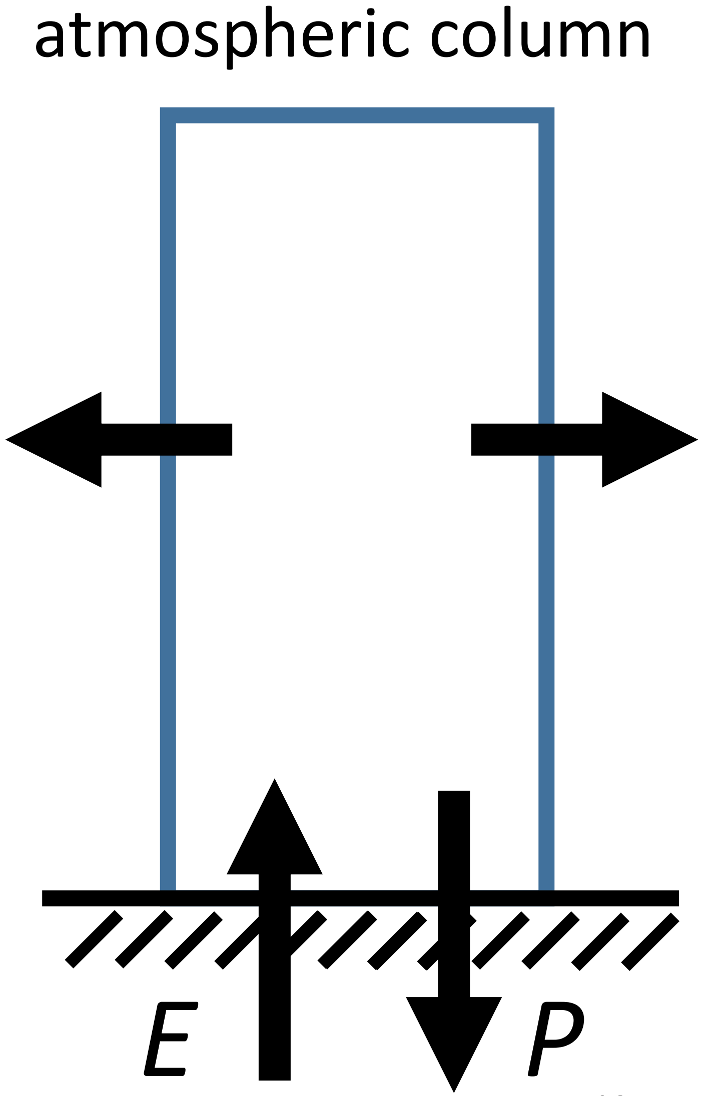
Each site represents an atmospheric column, and q represents it's water content.

This can change in three ways:

1. Surface evaporation E adds to q
2. Surface rain P subtracts from q
3. Lateral redistribution change q locally



Changing the rules

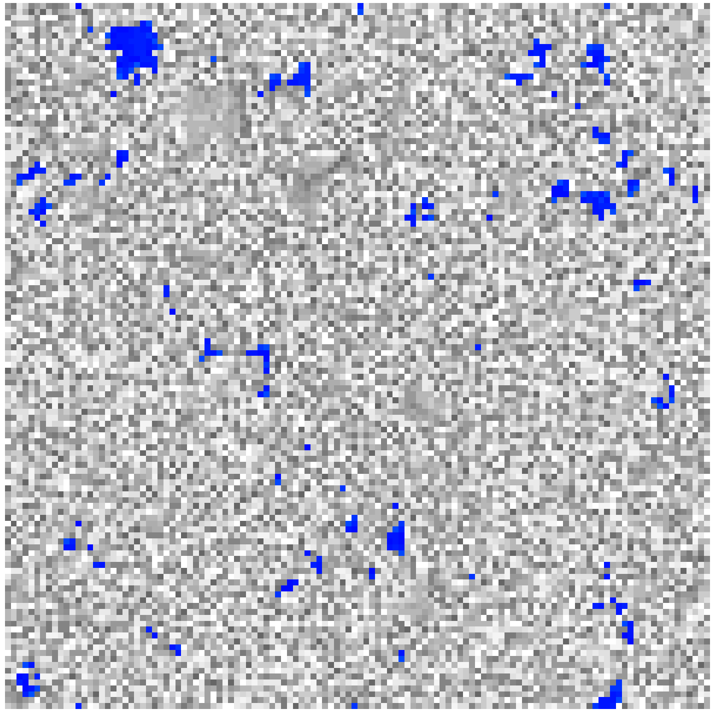


Modified model – Relation to convection

The model assumes:

- Convection triggers once q is a above a threshold, and stops once q falls below a lower threshold
- Evaporation is uniform in space and time
- Rainfall coincides exactly with convective activity
- Horizontal water transports only prevails near convective activity

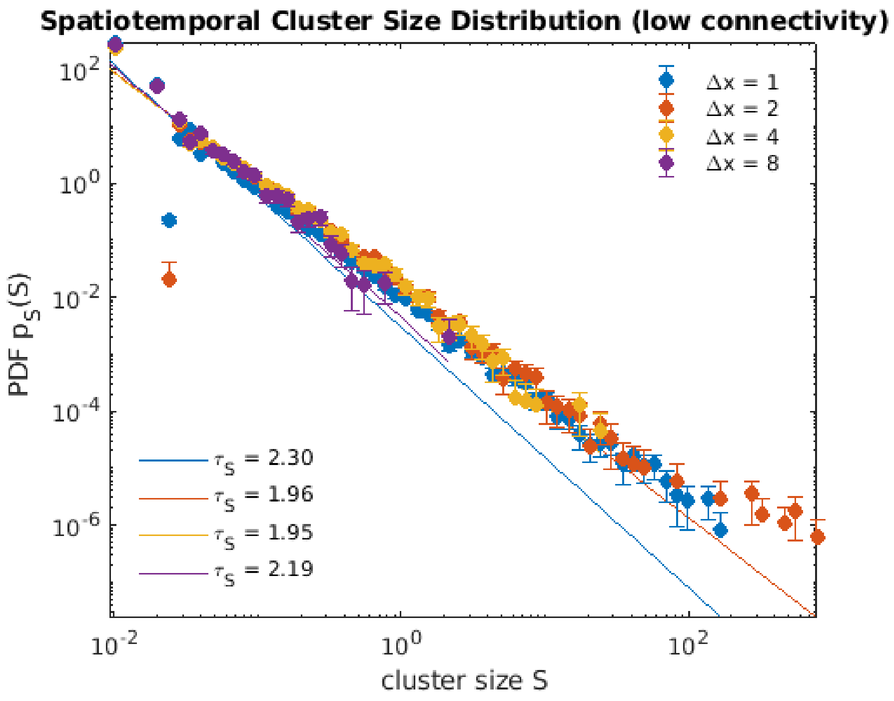
Modified model – Results



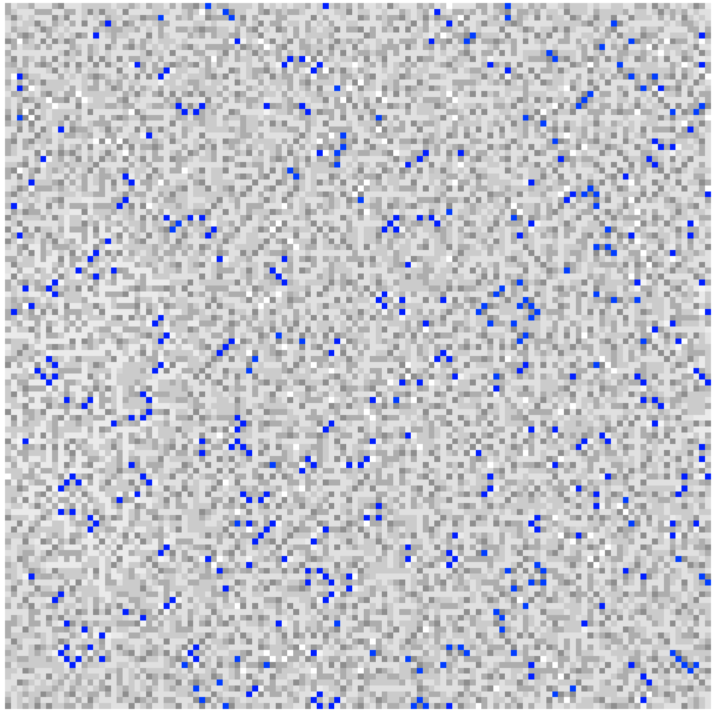
q-field in gray scale
(0 is black, 1 is white),
with *P*-field in blue on top.

The model can produce a large variety of sporadic rain clusters of many sizes.

The size distribution of spatiotemporal clusters follow a power law.



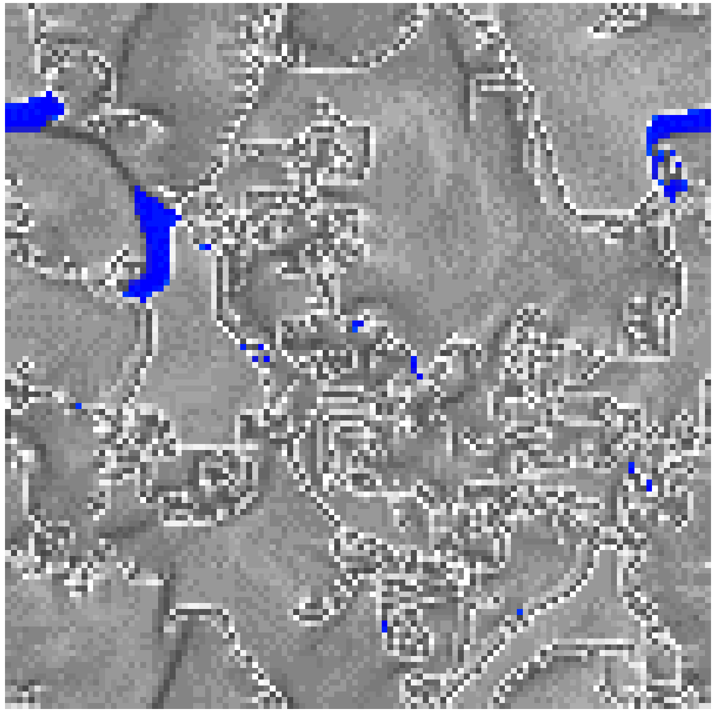
Modified model – Results



q′ high = short duration of activity

Varying deactivation threshold *q′*, the rain clusters in the model varies from

- **scattered** minimal clusters, evenly spaced on larger scales (left), over
- **sporadic** clusters of many sizes clumping together in space and time, to
- **aggregated** large clusters dominating the scene, ”eating up” moisture as they travel through the domain (right)



q′ low = long duration of activity

Water tranport & convection interplay

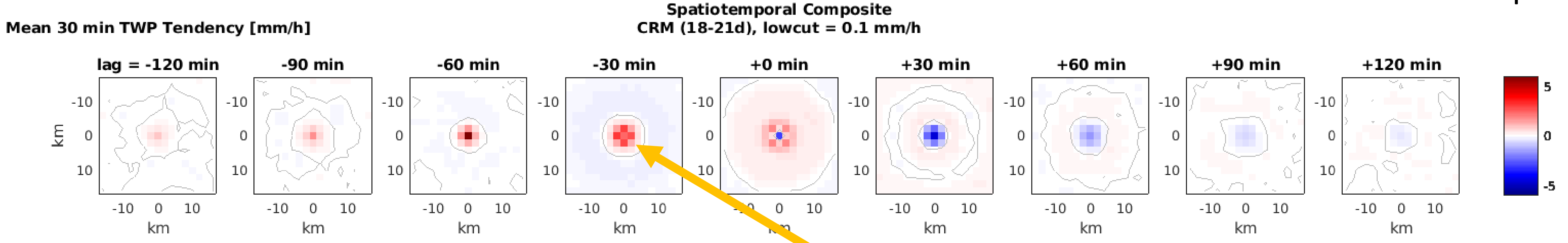
Cloud resolving model lessons

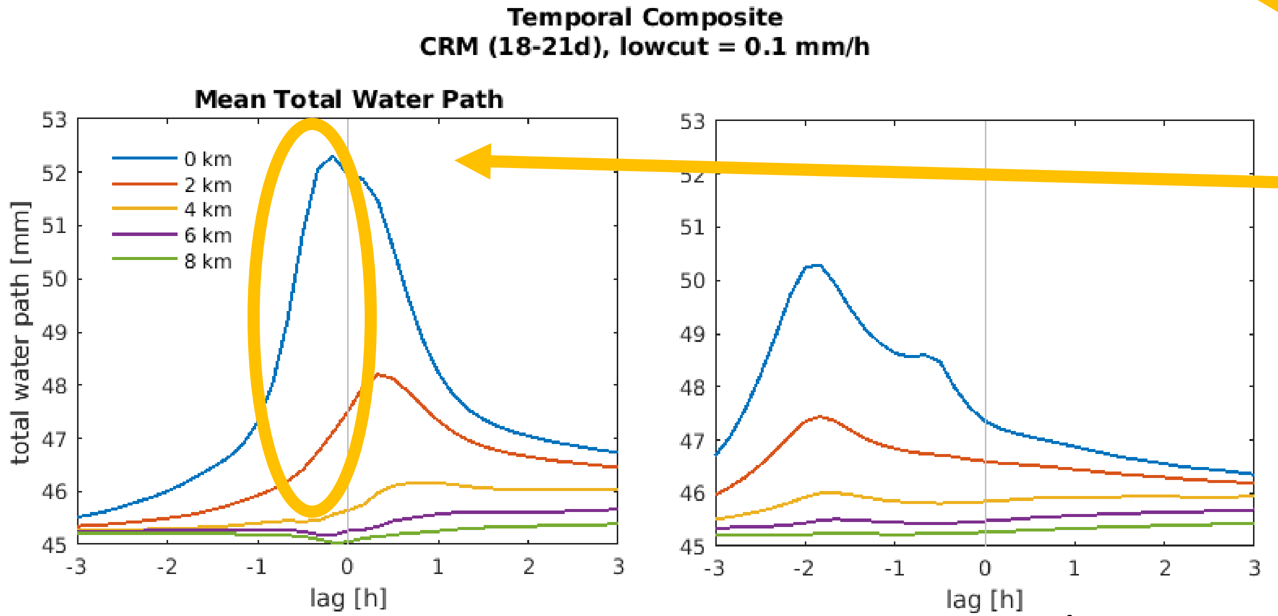
How does the convective scale water transport look around rain clusters?

We investigate cloud resolving model in radiative-convective equilibrium.

Cloud resolving model lessons

composite centered at beginning of rain incident of 30 min forward differece in total water path





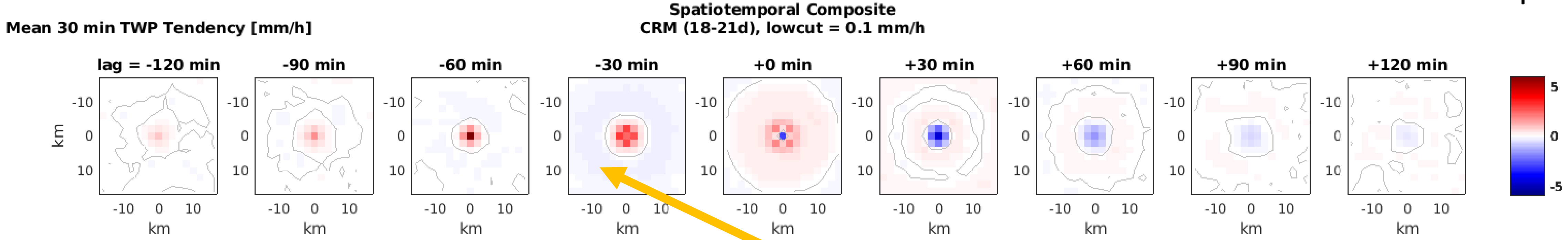
rain start

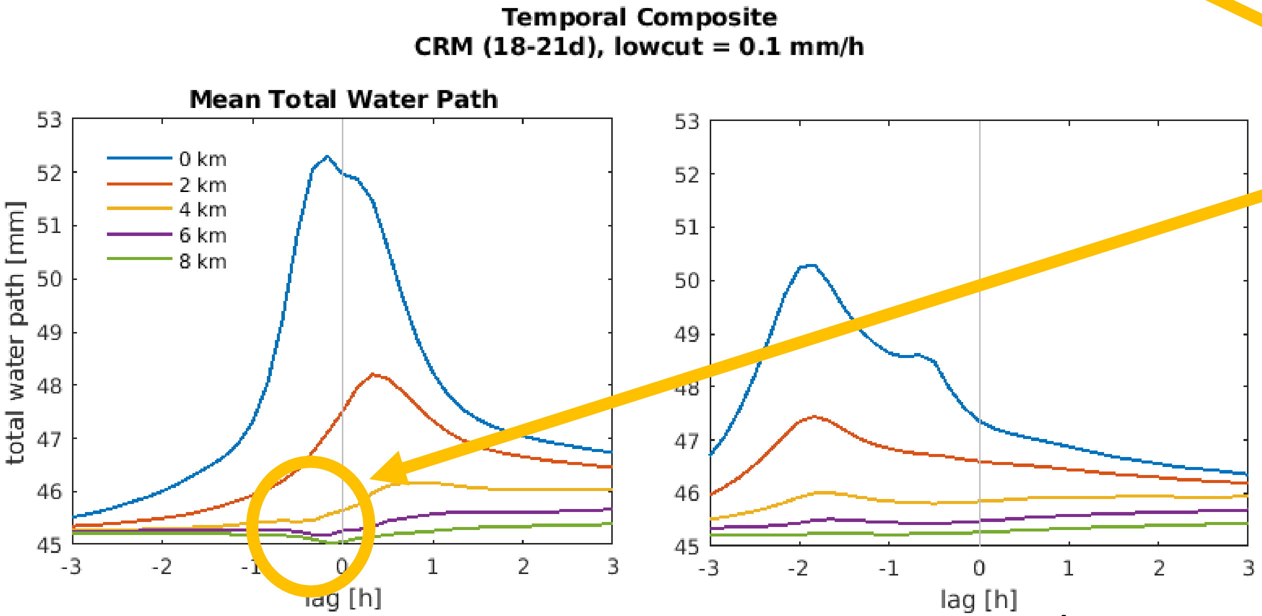
rain end

Convecting column moistens inner ~5 km leading up to rain

Cloud resolving model lessons

composite centered at beginning of rain incident of 30 min forward differece in total water path





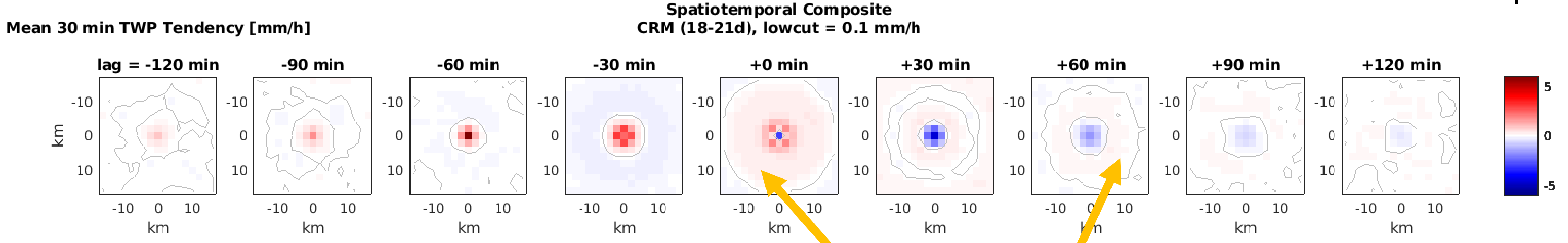
rain start

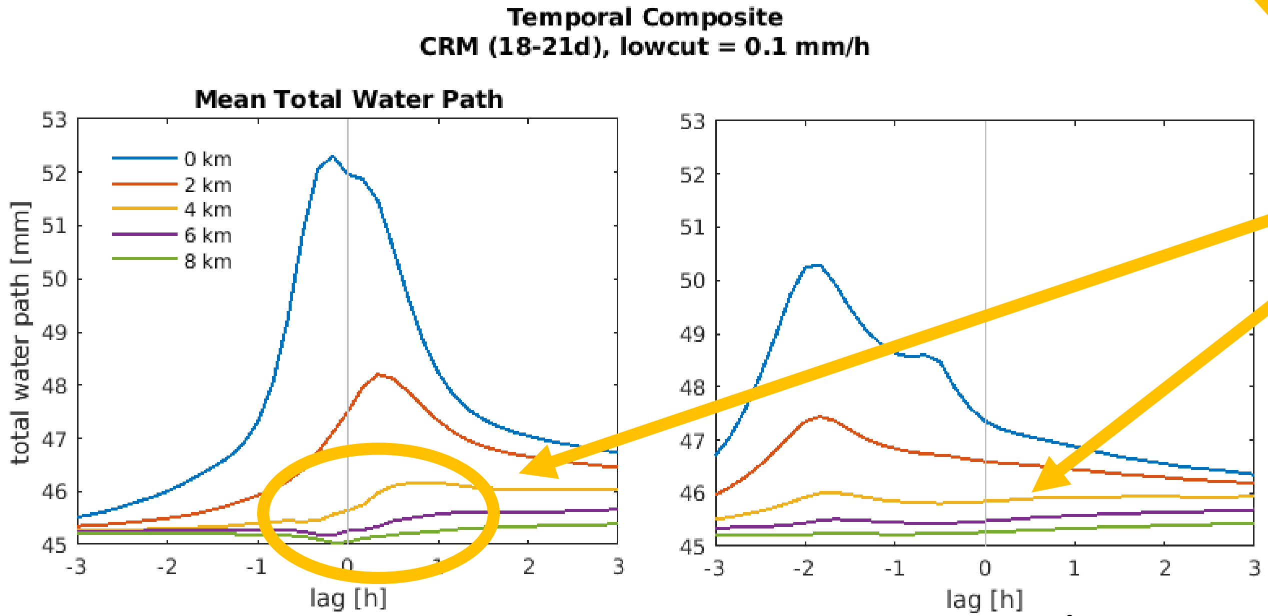
rain end

The moisture is partly ”borrowed” from ~10 km surroundings...

Cloud resolving model lessons

composite centered at beginning of rain incident of 30 min forward differece in total water path





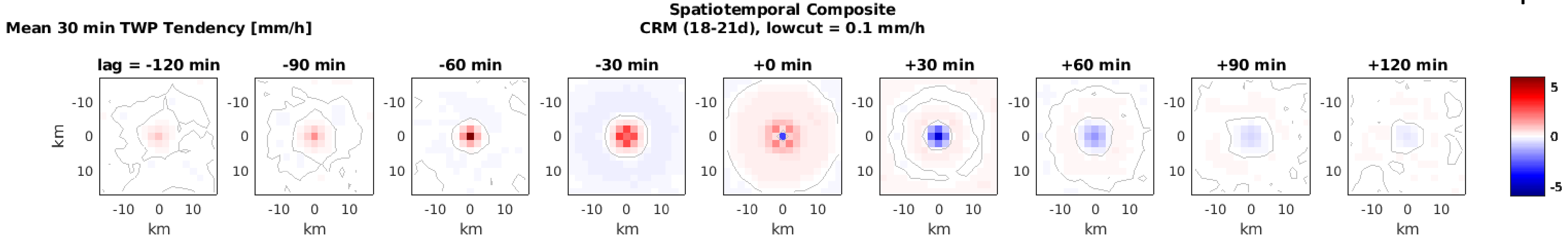
...then more than given back during and after rain.

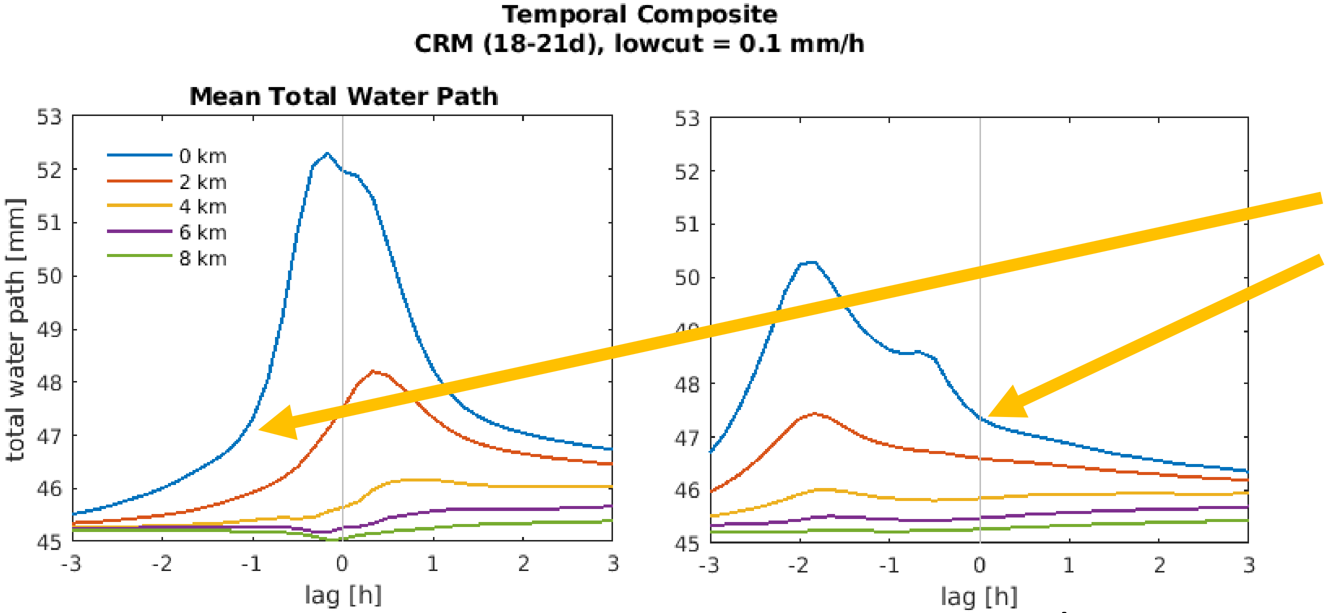
rain start

rain end

Cloud resolving model lessons

composite centered at beginning of rain incident of 30 min forward differece in total water path





rain start

rain end

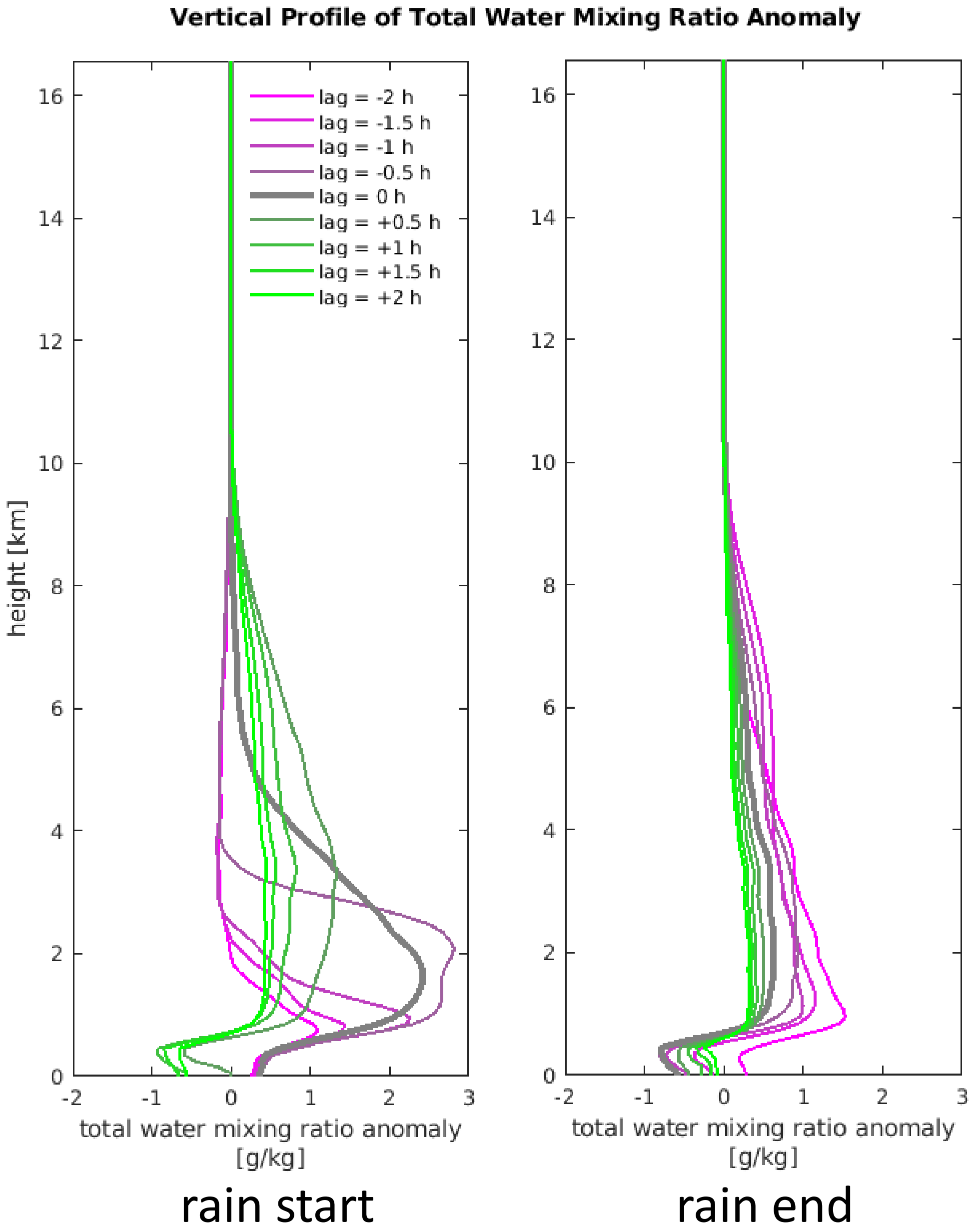
Note that the convecting column is about as moist after rain as ~1 h before rain!

kvc923@alumni.ku.dk

So is
activation threshold = deactivation threshold
afterall?

What if look at the vertical distribution?

kvc923@alumni.ku.dk



Filled up from below, then emptied from below.

- Before rain start, the water content of the lower troposphere rises, ”filling up” the column from the lowest levels and upward.
- At rain start, the boundary layer (lowest ~400 m) is quickly ”drained”, while the upper troposphere is moistened.
- During rain, the whole column is drained.
- After rain, the boundary layer moistens, while the upper column dries.

Lower layer is acting, upper layer is reacting?

Summary

- Tropical rainfall is hypothesized to be an instance of SOC.
  Can this be captured by a simple model?
- Take away from theoretical (modified SOC) modelling:
  Spatially and temporally extended clusters of activity is seen when

  deactivation threshold < activation threshold.
- Take away from cloud resolving simulations:
  Looking at the column integrated water content deactivation threshold ~= activation threshold! This might be resolved by vertical subdivision: Lower layer moisture is determinant of convective activation.

Reference

J. D. Neelin, O. Peters, J. W. B. Lin, K. Hales, C. E. Holloway: Rethinking convective quasi-eqilibrium: observational constraints for stochastic convective schemes in climate models, Phil. Trans. R. Soc. A, 2008