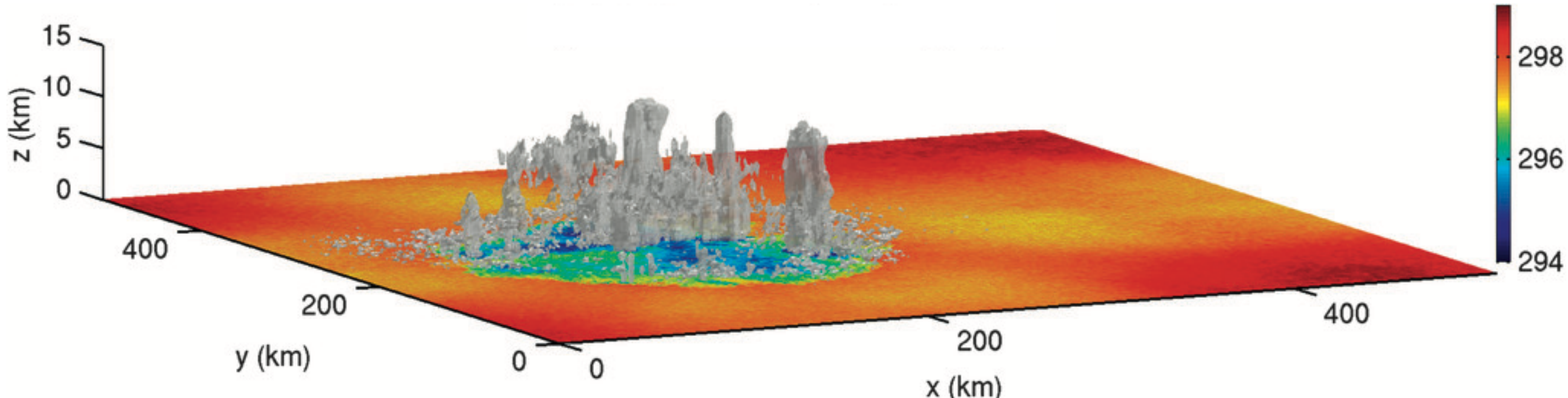
Convective aggregation in idealized stochastic models

Giovanni Biagioli[1,2] and Adrian Mark Tompkins[2]

[1]Università degli Studi di Trieste, Italy [2]Abdus Salam International Centre for Theoretical Physics (ICTP), Italy

The point of contention: scattered vs organized convection in CRM simulations

In cloud-resolving models (CRMs) run in radiative-convective equilibrium (RCE), tropical convection can spontaneously aggregate into one single localized moist region if the domain is sufficiently large, even despite homogeneous boundary conditions.



From *Muller and Held (2012)*

<u>CRM simulations identify some of the physical mechanisms driving convective clustering…</u>

So far so good…But there is a "but"

QR code for OSPP contest

Sharing is encouraged

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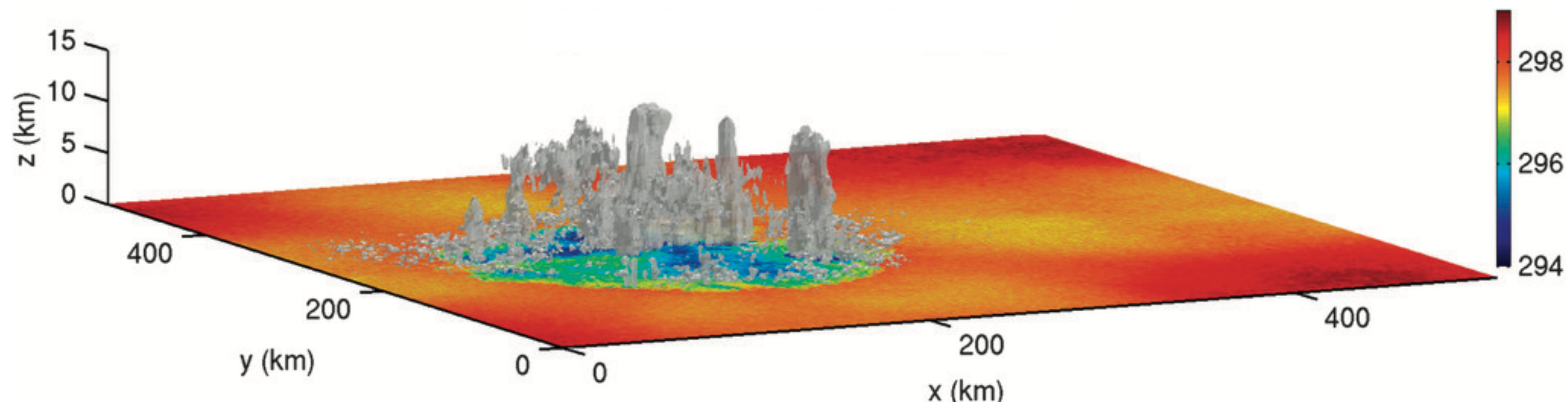

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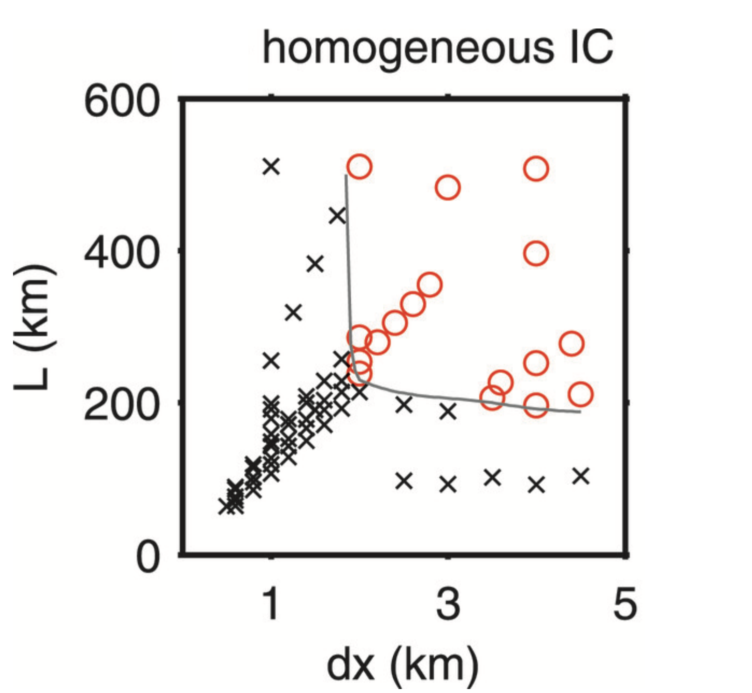

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- The occurrence of organization may depend on the model physics, setup (e.g., L, Δx) and parameterizations.
- Models do not often agree on the nature and details of organization 🤔

💡 **So why not using simpler models reproducing aspects of the more complex ones?**

If a simple, idealized model provides robust results, then we may try to use them to understand and explain the sensitivities detected in CRM simulations.

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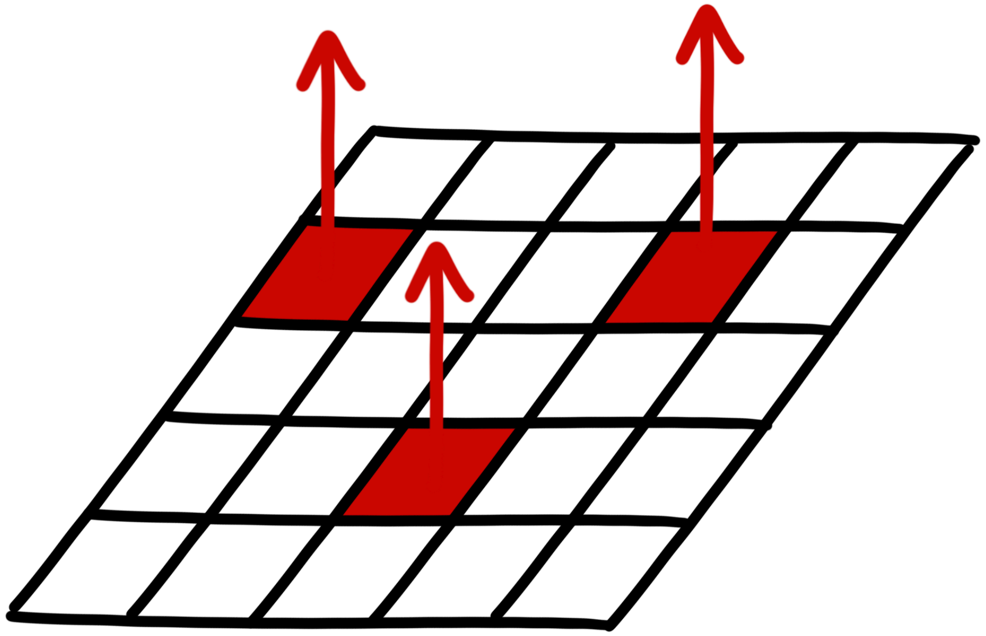
Our simple model of tropical convection

- The model is based on the work by Craig and Mack (2013), but enriched with important novelties.
- In each column of the domain, the budget of column (total water) relative humidity (CRH), $R = R(\mathbf{x}, t)$, is modeled as

$$\frac{\partial R}{\partial t} = \underbrace{\frac{1}{\tau_{\mathrm{c}}}(R_{\mathrm{d}} - R)\underbrace{1_{\mathrm{c}}(p_{\mathrm{c}}(R))}_{\text{new!!!}}}_{\text{convective moistening}} + \underbrace{K\,\nabla^2 R}_{\text{diffusion}} \underbrace{- \frac{R}{\tau_{\mathrm{sub}}}}_{\text{subsidence}}$$



↑ Only where the indicator function $1_{\mathrm{c}} = 1$, is convection occurring.

WHERE, WHEN AND HOW IS THE INDICATOR FUNCTION SWITCHED ON?

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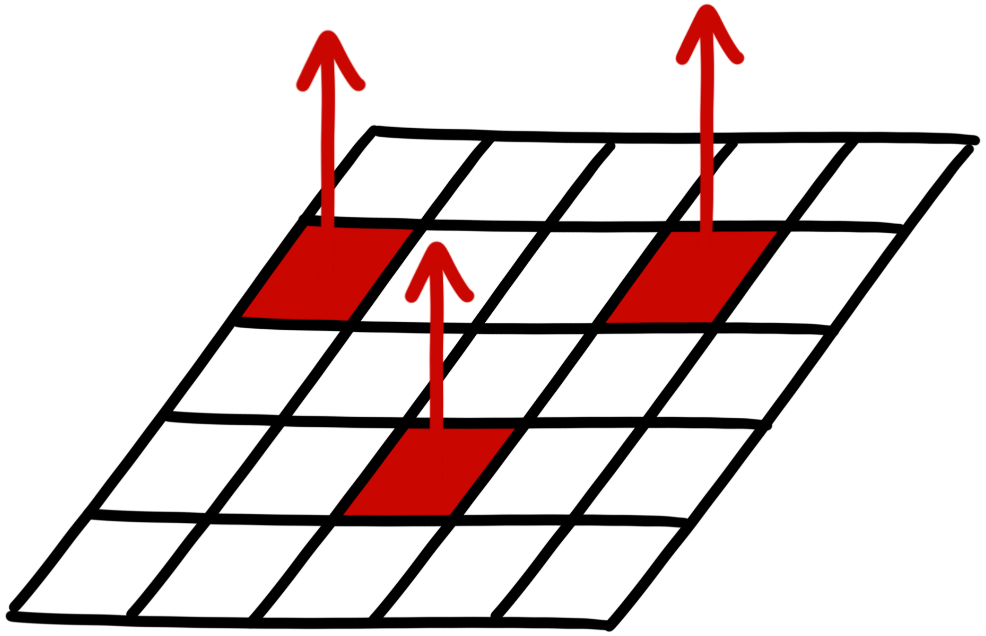

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WHERE, WHEN AND HOW IS THE INDICATOR FUNCTION SWITCHED ON?

- The number $N_c = N_c(t)$ of active convective locations per time step is imposed as an external constraint.
- The time-averaged convective population size is provided by a scaling argument by Tompkins and Craig (1998): to obey continuity, the cumulus fraction σ must satisfy

$$(1-\sigma)\,w_{sub} + \sigma w_c = 0 \Rightarrow \sigma = \frac{|w_{sub}|}{w_c} = \frac{h}{\tau_{sub}}\frac{1}{w_c} \Rightarrow \overbrace{\bar{N}_c = \left(\frac{L}{\Delta x}\right)^2 \frac{h}{\tau_{sub}}\frac{1}{w_c}}^{\text{IMPORTANT!!!}}.$$

- Are the N_c cells sampled completely at random? No!, according to a PDF based on the moisture-precipitation relationship by Bretherton et al. (2004):

$$p_c(R) = C\exp\left(a_d R\right).$$

<u>This means that the model contains the feedback between convection and water vapour.</u>

The model manages to mimic convective clustering

TYPICAL EXPERIMENTAL SETUP

- Doubly periodic domain with size $L = 300$ km and spacing $\Delta x = 2$ km. Horizontally homogeneous initialization, $R_0 = 0.8$.
- $K = \mathcal{O}(10^4)$ m^{2}s^{-1}, $\tau_{\text{sub}} = \mathcal{O}(20)$ days, $a_d = 14.72$ (TRMM retrieval version 7).

Depending on the parameter setting, the model produces either random 🍿 or aggregated states. Look…

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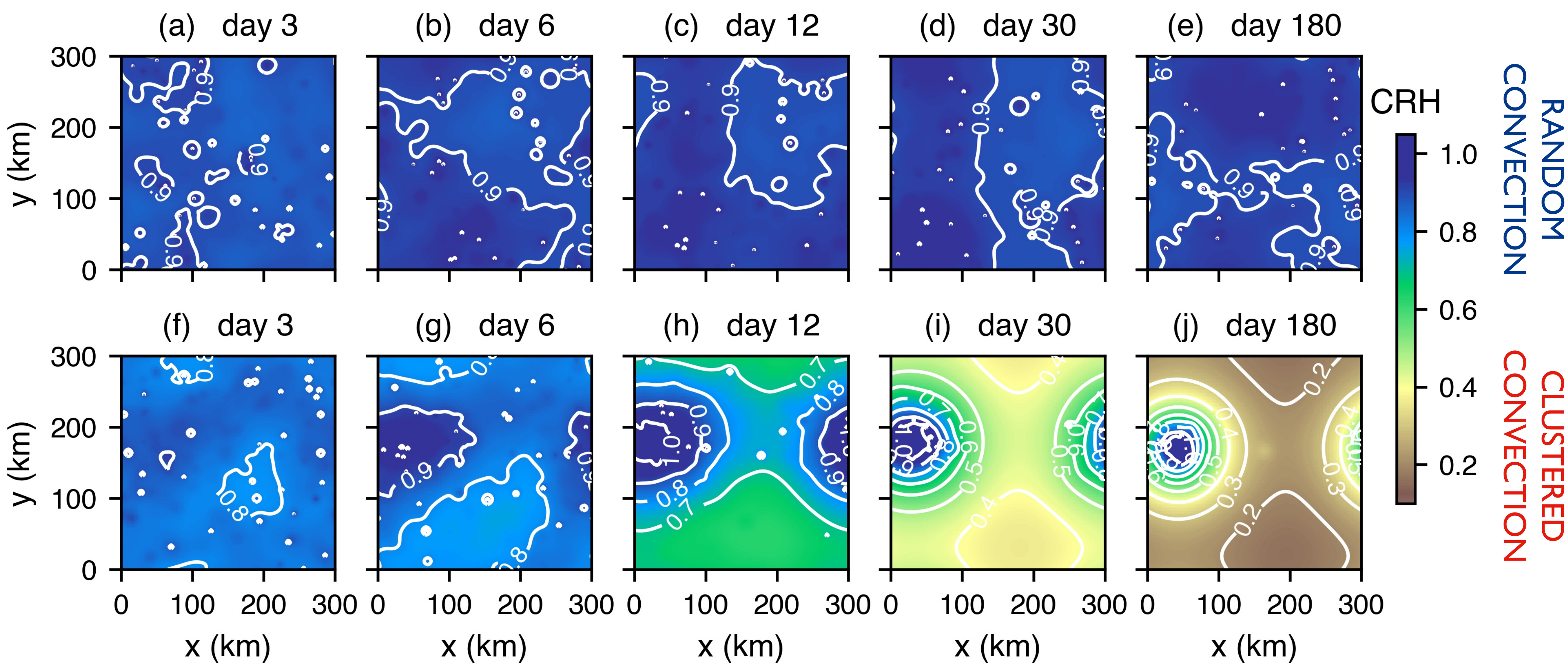
*Snapshots of CRH field for $K = 10^4$ **m²s⁻¹ (top panels)**, 5×10^3 **m²s⁻¹ (bottom panels)**, $\tau_{\text{sub}} = 14$ days, a_d, L, Δx, R_0 kept at their default values.*



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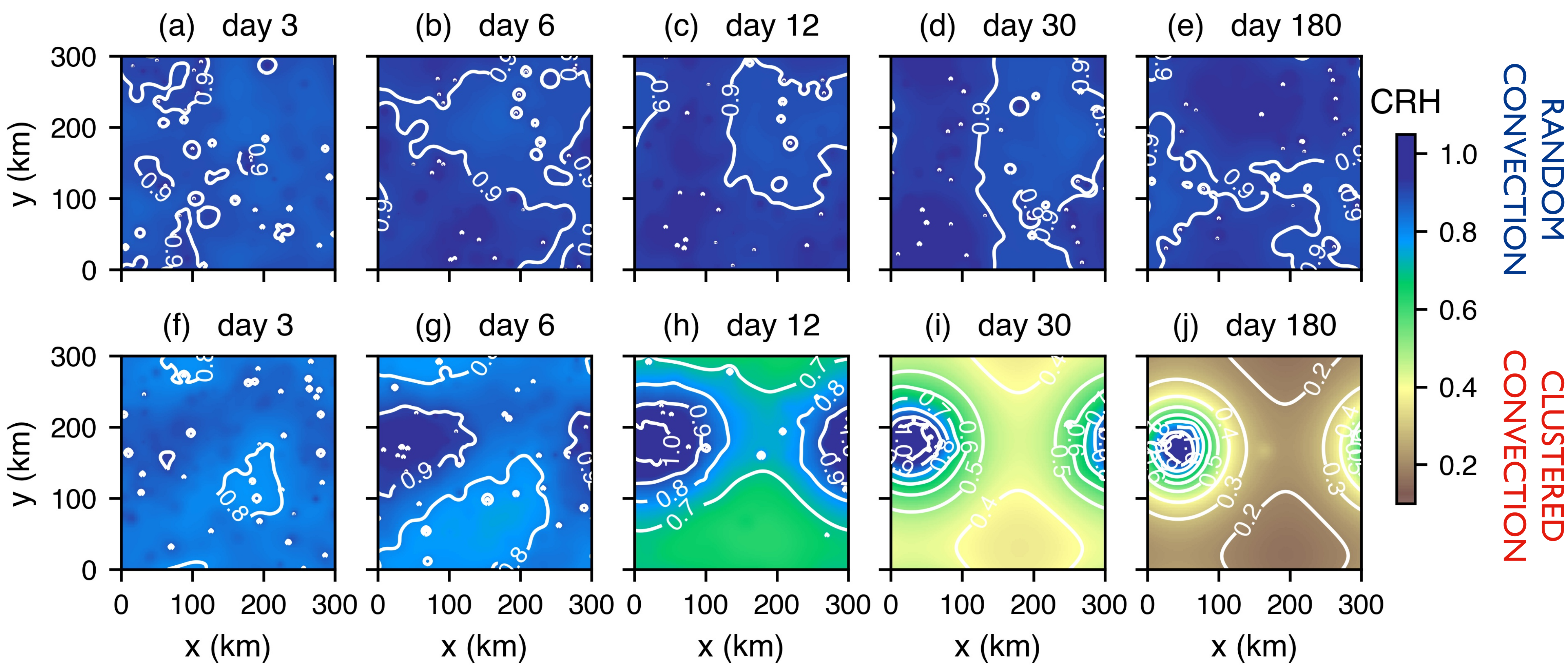
Snapshots of CRH field for ***$K = 10^4$ m^{2}s^{-1} (top panels)****,* ***5×10^3 m^{2}s^{-1} (bottom panels)****, $\tau_{sub} = 14$ days, a_d, L, Δx, R_0 kept at their default values.*



What is this telling us? The occurrence of organization is sensitive to the value of K!!!

WHICH ARE THE INGREDIENTS TO EXPLAIN THE TRANSITION?

- The key parameters K, τ_{sub}, a_d (aggregation favored by lower diffusion/more vigorous subsidence/stronger feedback).
- Details of the experimental configuration L, Δx (clustering facilitated by larger domains/coarser resolutions).

A dimensionless parameter to explain the state transition

…before deriving it, it is important to say that…

…the **maximum distance between updrafts** $d_{\text{max,clr}}$ (or, relatedly, the maximum inter-convective NN distance $d_{\text{max,nn}}$) **in the pre-organized stage** could be important and can explain the sensitivities to both L and Δx. It can be easily calculated assuming the initial random sampling of points as the restriction of a homogeneous Poisson process to a compact set.

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◉ Using scaling arguments and fits from empirical data, we introduce the parameter, termed **aggregation number**,

$$\gamma = \frac{K\tau_{\text{sub}}}{a_d^2 L \bar{d}}$$

← Area of influence of an individual event (a_d^2)

← Expectation of $d_{\text{max,nn}}$ ($\bar{d}$)

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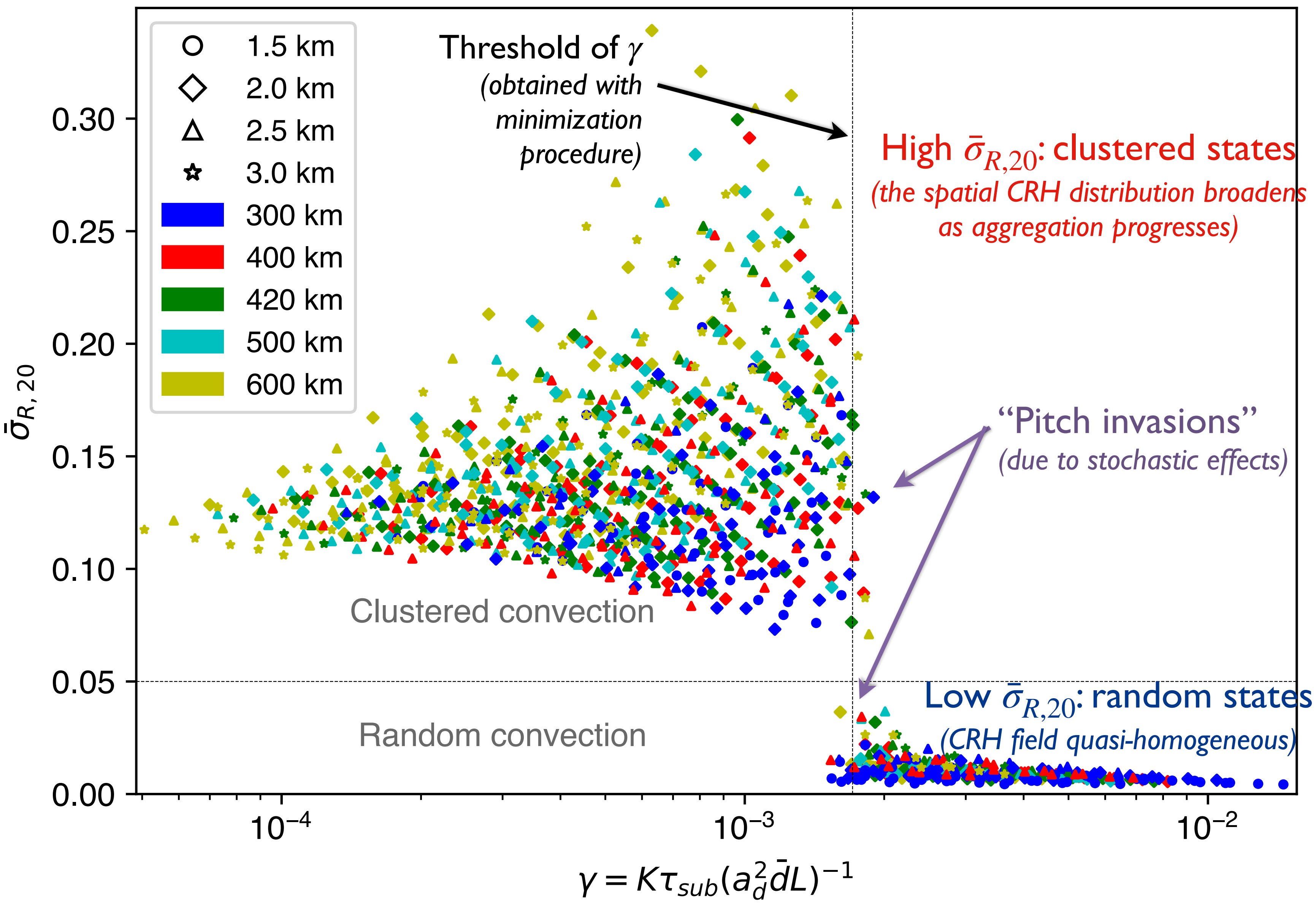
End climate for different values of K, τ_{sub}, a_d, L (colors), Δx (markers)



Runs with different values of the parameter γ, each associated with the corresponding value of $\bar{\sigma}_{R,20}$, i.e., the spatial CRH std averaged over the last 20 (out of 180) days of simulation.

- The parameter incorporates the model processes, domain size and resolution ✅
- The value of γ robustly indicates whether a specific model and experiment setup would result in self-organized state (that is, when $\gamma < 1.7 \times 10^{-3}$).