Sources of heterogeneity for convection and some implications

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Closure: the basic idea

- To predict the amplitude of expected convective activity as a function of space and time
- Assume we measure amplitude with the cloud-base mass flux, M_B
- Could go further to predict the partition of $M_B = \sum M_{Bi}$ but not considered here

Traditional formulation: budgeting

- Consider some function f of the large-scale variables φ and the convective-scale variables φ_c and mass flux profile η
- Integrate this over some range of heights,

$$I = \int f(\varphi, \varphi_c, \eta) dz$$

- We can make a closure from stationarity of this quantity, $\partial I / \partial t = 0$
- Or from a relaxtion

General closure structure

- Take a time derivative of the definition, and substitute for $\partial\varphi/\partial t, \partial\varphi_c/\partial t$ and $\partial\eta/\partial t$ using equations developed from the mass flux framework
- After some algebra,

$$\frac{\partial I}{\partial t} = F - D$$

- F is large-scale generation or “forcing”: terms independent of M_B
- D is consumption by convective processes: terms dependent on M_B, proportional for entraining plumes with simple microphysics

Examples: Moisture Closure

- Moisture closure for $f = \rho q$

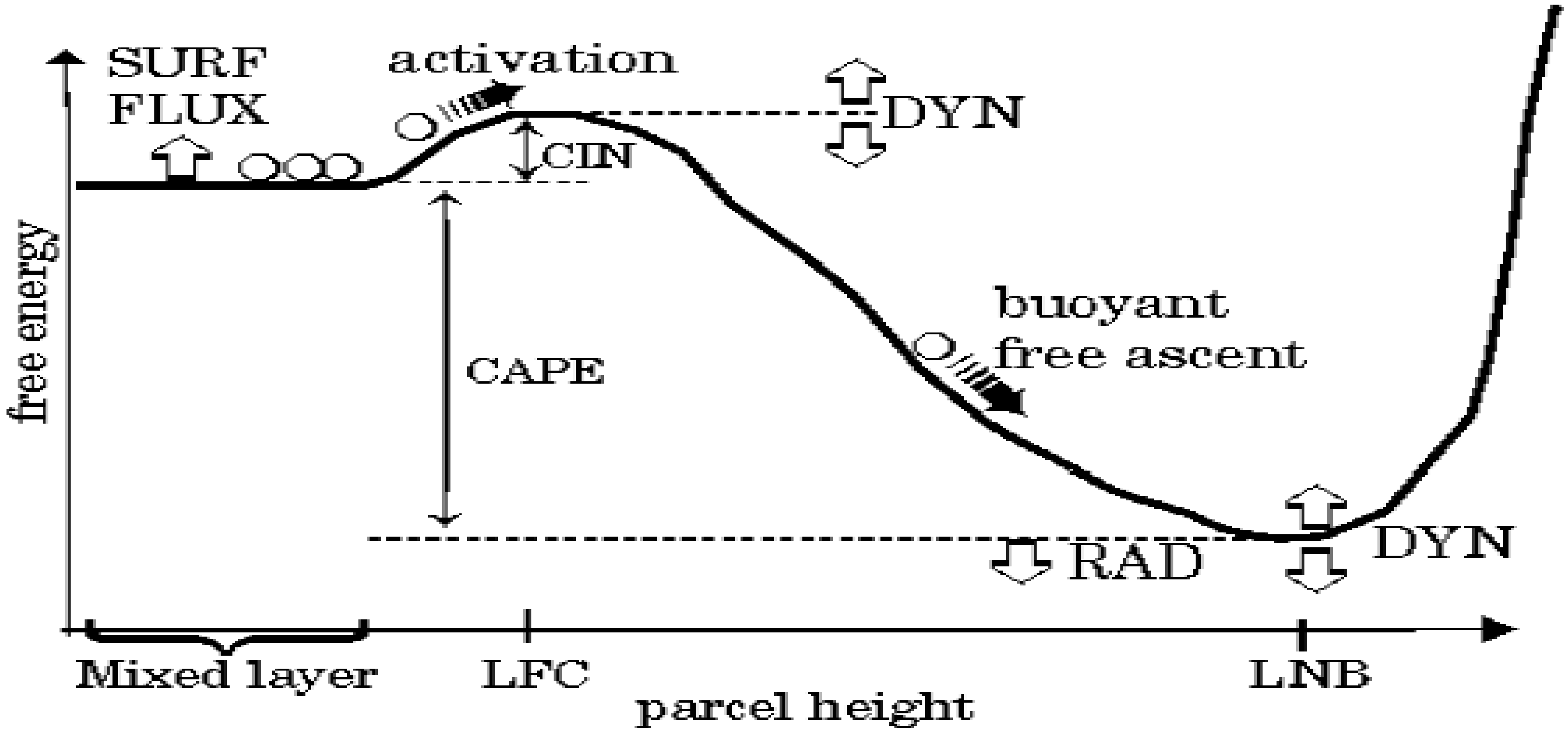
$$F = \text{moisture convergence} = -\int_0^{z_T} \nabla.\rho\mathbf{u}q dz + E$$

$$D = M_B \int_{z_b}^{z_T} \eta \left[\delta_c (q_c - q) + \frac{\partial q}{\partial z} \right] dz$$

Other examples

- CAPE closure with $f = b$, the buoyancy for non-entraining parcel ascent
- PCAPE closure with $f = \rho b$ (Bechtold et al 2014)
- Cloud work function, $f_i = \eta_i b$
- CIN closure as per Comorph (to an extent)

Alternative from Mapes (1997)



"clearly the situation is hopeless in detail" $\Longrightarrow M_B = f(\mathrm{CIN})$

Comments on CIN/BL methods

- Traditional closures enforce an equilibrium
- Here an equilibrium arises from initation of many individual events
- How many must be established by the need for a self-consistent BL state
- One caution in interpretation is that all mass flux schemes consider a lifetime-average from the start
- In an actual homogeneous equilibrium case, we don't care so long we reach a stable equilibrium

Scale dependency: a trivial case

- Consider a truly homogeneous area subjected to an imposed truly homogeneous destabilization (forcing)
- The closure should deliver the same estimate of expected activity per unit area, $m_B = M_B/A$ at all times and all locations
- Δx or Δt should be irrelevant

Heterogeneity is non-trivial

1. Convection not smooth: homogeneous case is heterogeneous viewed on a scale where $N \not\approx \infty$
2. Forcing is heterogeneous (even before any convection occurs)
3. Convective activity feeds back on other convection in the vicinity which may amplify or upscale the intrinsic granularity (e.g., cell merging, cold pool interactions)
4. Convection feeds back to the forcing so that this becomes heterogeneous (e.g., radiative interactions in self-aggregration simulations)
5. The enviroment is heterogeneous (e.g. it has topography)

Scale dependence with heterogeneity

What does good scale dependence mean in this situation?

If heterogeneity is characterized by a scale L_{het}, necessary that...

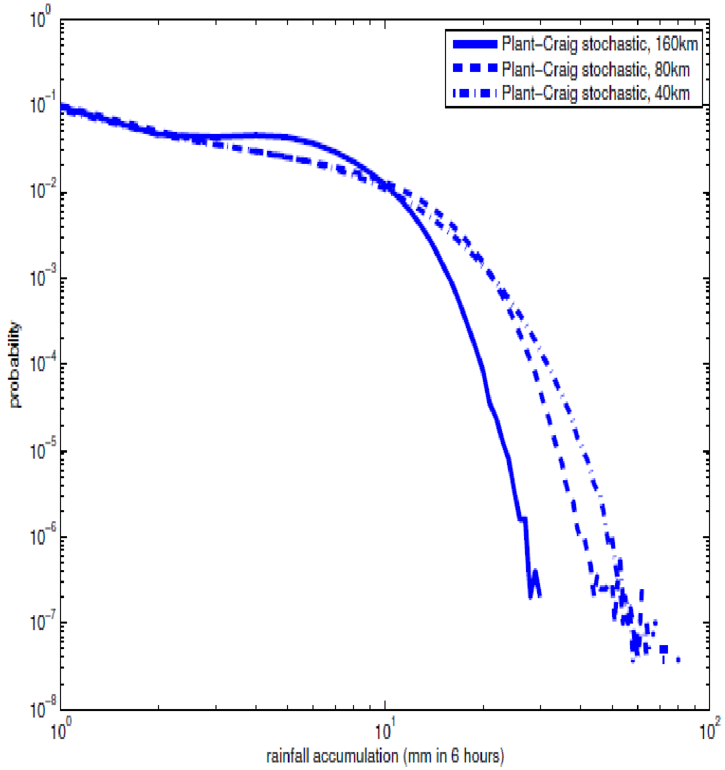
- Our method should agree about M_B/A for different Δx if we average to $L \gg L_{\mathrm{het}}$
- Our method should agree about M_B/A for different Δx if we look on scales $L \ll L_{\mathrm{het}}$

Convection not smooth

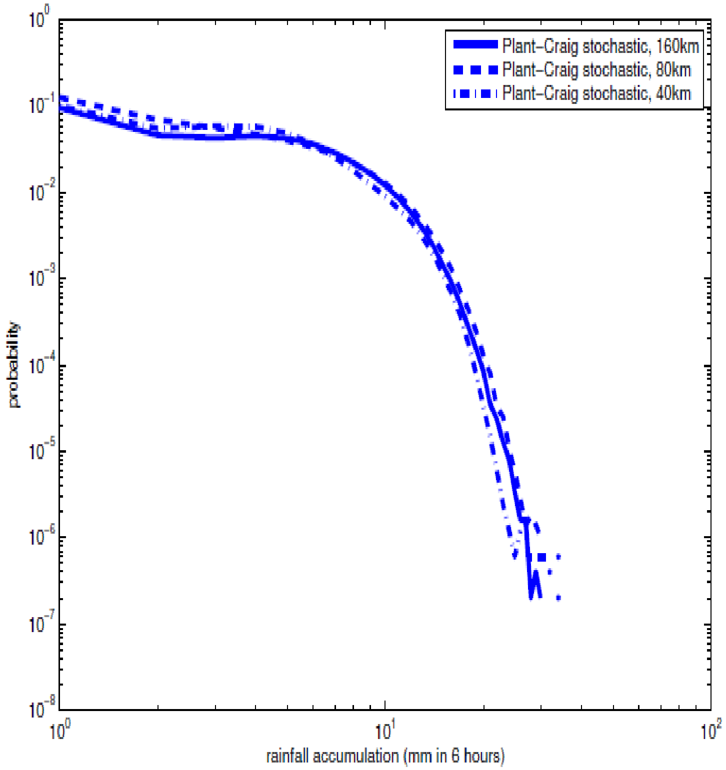
1. Convective activity is not smooth
   - The simplest non-trivial case: a (mostly) solved problem
2. Forcing is heterogeneous
3. Local feedbacks
4. Convection induces heterogeneous forcing
5. The enviroment is itself inhomogeneous

Example of resolution-independence

Keane et al (2013): ie. aqua-planet 6 h rain-rate pdf is resolution independent with consistent averaging strategy



pdf on native grid



pdf on 160km grid

Also Keane and Plant (2012), Sakradzija et al (2016)

Why it works

- The heterogeneity is being introdued stochastically
- The stochasticity is based on a *countable number* of centres of activity
- $\implies$ the stochasticity can be evaluated indpendently over any area of interest
- Adapts properly and automatically to resolution because $N \sim A$

Also BL variability in CPMs: Rochetin et al (2014), Kober and Craig (2016), Clark et al (2018)

Heterogeneous environment

1. Convection not smooth
2. Forcing is heterogeneous
3. Local feedbacks
4. Convection induces heterogeneous forcing
5. The enviroment is heterogeneous
   - *In principle* easy to deal with: need to measure how convective activity is systematically different (say) over topography (Kirshbaum et al 2018)

Heterogeneous forcing

1. Convection not smooth
2. Forcing is heterogeneous
   - This case has largely dominated thinking on closure, and existing forms of closure are not an unreasonable approach towards this
3. Local feedbacks
4. Convection induces heterogeneous forcing
5. The enviroment is heterogeneous

Traditional closures

1. Convection not smooth
2. Forcing is heterogeneous
   - Intended to handle this case
   - But perhaps not very well
3. Local feedbacks
   - Little or nothing to offer here
4. Convection induces heterogeneous forcing
   - Probably fail to capture these behaviours well
5. The enviroment is heterogeneous

Mechanistic BL approaches?

1. Convection not smooth
2. Forcing is heterogeneous
3. Local feedbacks
   - dominated by convection/boundary-layer interactions?
   - if so, it seems attractive to develop BL-focussed closures to capture them
4. Convection induces heterogeneous forcing
5. The enviroment is heterogeneous

Mechanistic BL approaches?

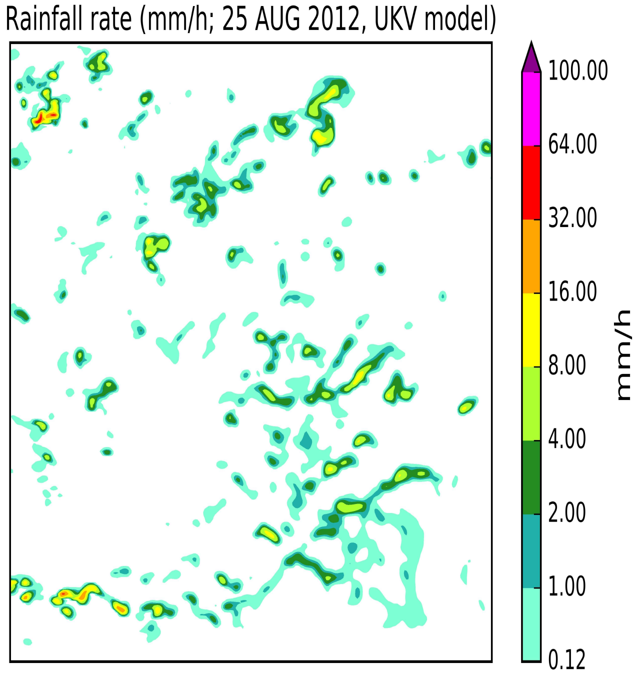
1. Convection not smooth
    - unnecessary but should not be damaging
2. Forcing is heterogeneous
    - Better, worse, or just different?
    - If BL-troposphere interactions strong enough, we only need to know about one of the two
3. Local feedbacks
    - Do we see real improvement here? Not obvious, but bar is very low
4. Convection induces heterogeneous forcing
    - Potential improvements here?
5. The enviroment is heterogeneous

More important: case 2 or case 3?

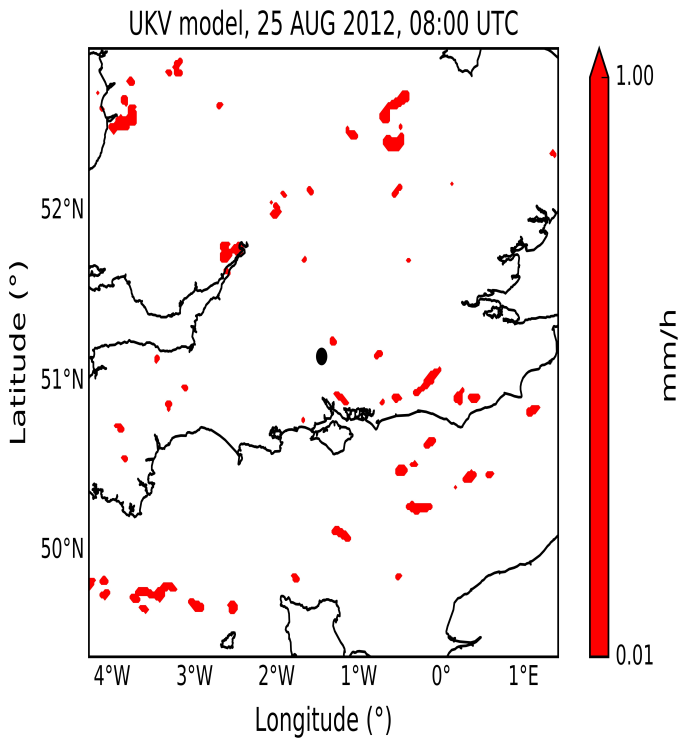
it can be difficult to sustain an empirical description between a process of dependent events in a homogeneous environment and one of independent events in a heterogenous environment

Diggle (2014) “Statistical analysis of spatial and spatio-temporal point patterns” p179

An example



snapshot of rain rates



55 convective clouds

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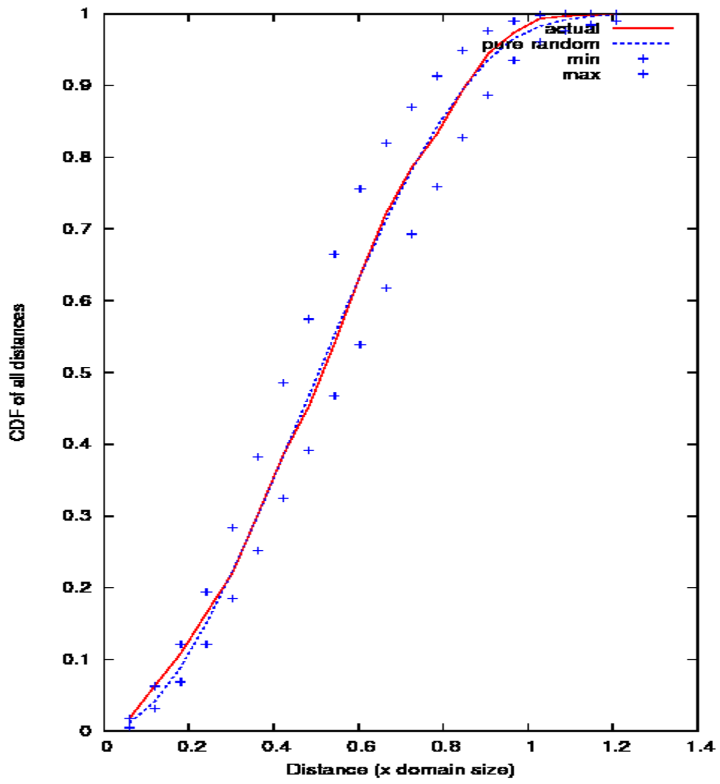
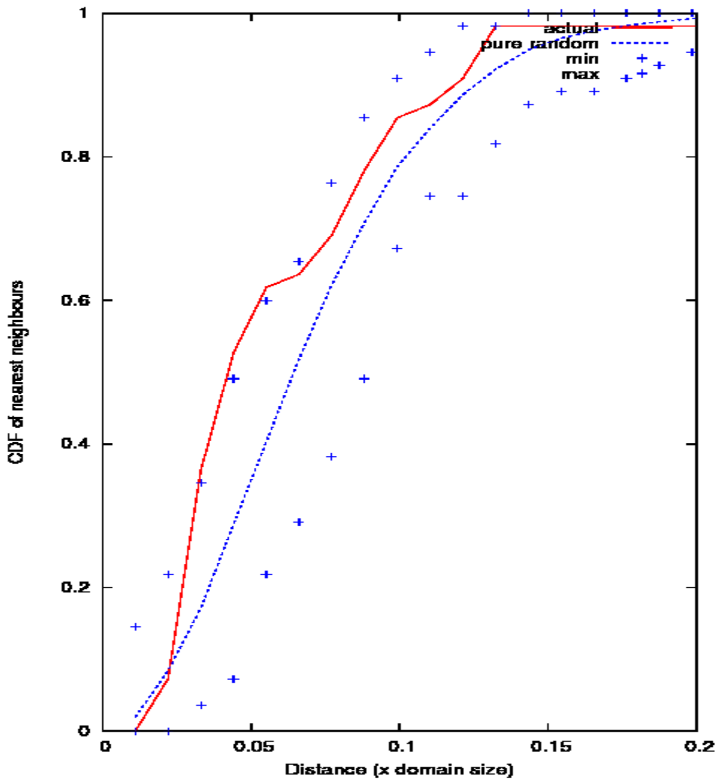
Non-random

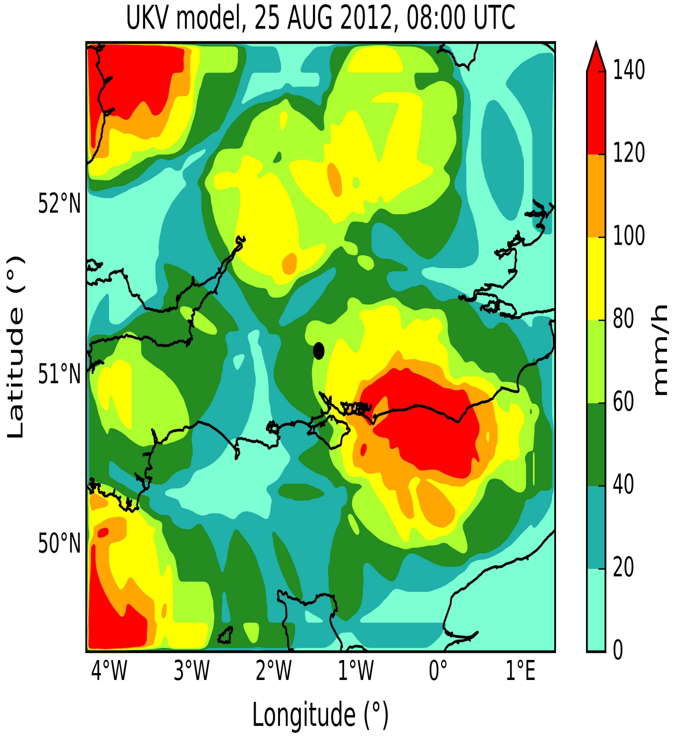


CDF of cloud separations



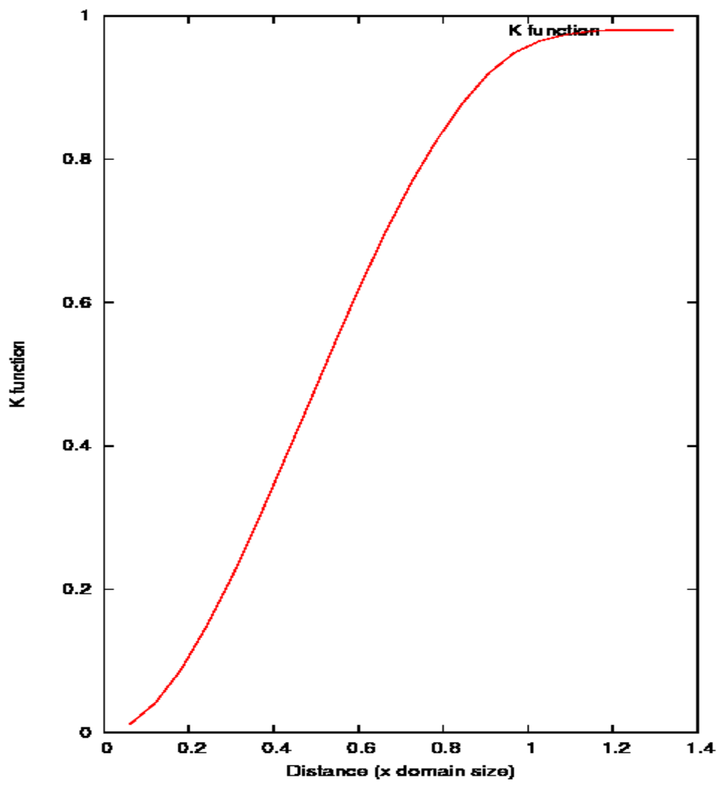
CDF of neighbours

Varying forcing



- Results can be "explained" by a Poisson process with a strength that varies spatially
- i.e. by a heterogeneous forcing

Cloud interactions



- Results can be "explained" by a non-trivial pair correlation function
- This can be reinterpreted in kinetic theory as producing an interaction potential
- i.e. convection as a non-ideal gas (Davies 2008, Rasp and Craig 2018)

Summary

- Homogeneous forcing is not such a bad assumption
  - except we probably don't evaluate it as such
- For heterogeneous cases it is genuinely hard to distinguish between
  - a spatially varying forcing
  - self-interactions of convective cells
- To get interactions right do we...
  - represent BL-mediated interactions explicitly (e.g. cold pool representation)?
  - represent some simplified signature of pre-existing convection (org parameter, memory prognostic, prognostic closure)?
  - characterize an interaction potential (how)?