Stochastic parameterization: Uncertainties from Convection

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ECMWF Workshop

Representing model uncertainty and error in numerical weather and climate prediction models

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Typical convective parameterization

Traditional framework

The Arakawa and Schubert (1974) picture

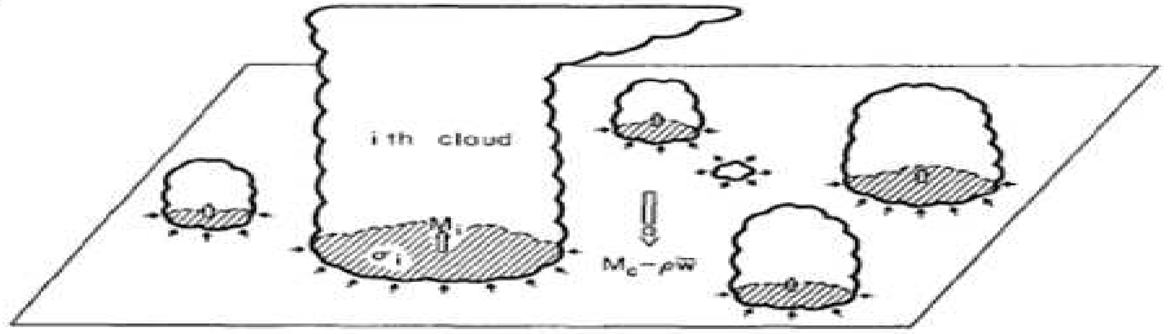


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

- Convection characterised by ensemble of non-interacting convective plumes within some area of tolerably uniform forcing
- Individual plume equations formulated in terms of mass flux, $M_i = \rho\sigma_i w_i$

Traditional framework

- An equilibrium picture: stabilization from the ensemble of plumes balances destabilization from large-scale forcing
- If plume equations are linear in mass flux then can sum over plumes and approximate ensemble with a representative "bulk" plume
- Microphysics is supposed to be crude by construction
  - and even cruder under a bulk approximation

Uncertainties from convection

1. structural: using the wrong equations
2. parameter: entrainment rate is the source of largest uncertainty in multi-parameter experiments like `climateprediction.net`
    - an entrainment rate is itself a parmeterization of cloud-environment interactions within the convective paremeterization and has major structurally uncertainties
3. an inherently uncertain process: a given “large-scale” state is consitent with many sub-grid states

The physics of fluctuations

Utterly trivial example

- Practical approach: seems desirable to introduce noise to improve spread-error realationship
- But the introduction of a stochastic component to our model equations cannot be agnostic about the physics of the fluctuations
- For example,

$$\frac{\partial\theta}{\partial t} + \underline{u}.\underline{\nabla}\theta = P_\theta(X,\alpha) + \varepsilon$$

P_θ is determinstic parameterization; α are parameters; X is the resolved-scale state; ε is noise

Change of variables

- Consider a change of variables to $\chi = e^{\theta}$

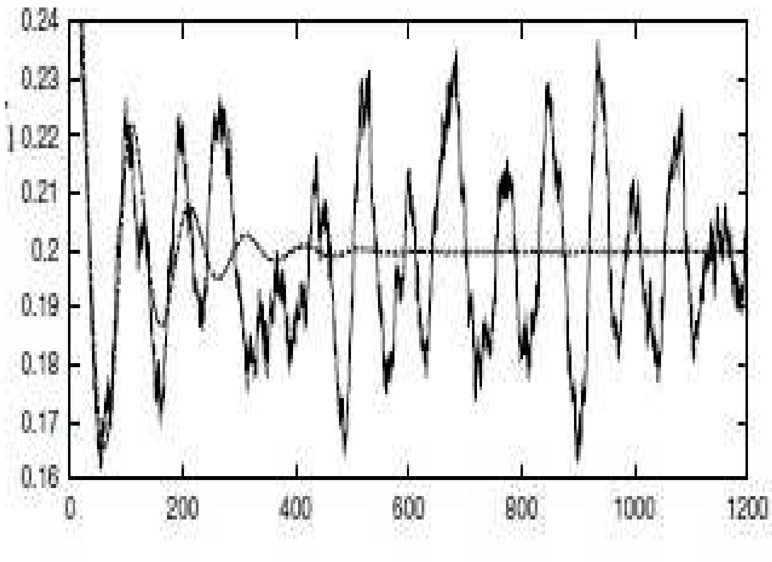
$$\frac{\partial \theta}{\partial t} + \underline{u}.\underline{\nabla}\theta = P_{\theta}(\theta, \alpha) + \varepsilon$$

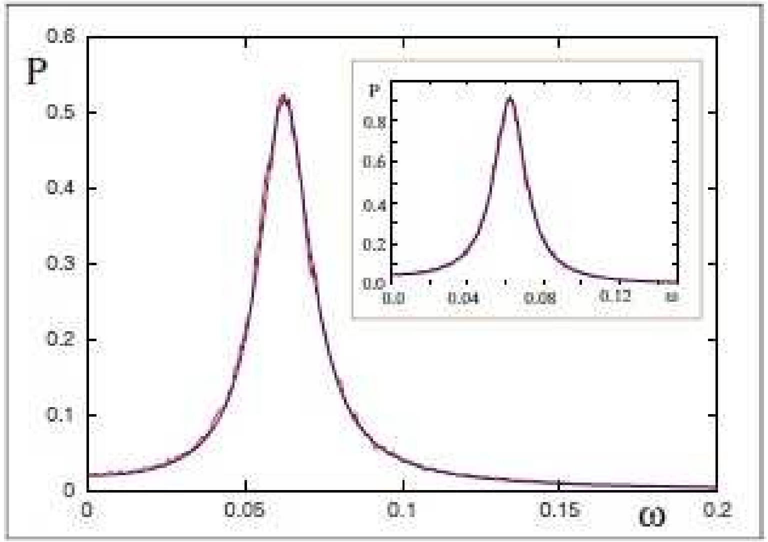
$$\frac{\partial \chi}{\partial t} + \underline{u}.\underline{\nabla}\chi = P_{\chi}(\chi, \alpha) + \varepsilon\chi$$

- Additive noise becomes multiplicative noise
- These names are meaningless in themselves:
  - have to ask additive or multiplicative in what?
  - and with what physical justification?

Example I: amplified stochastic cycles

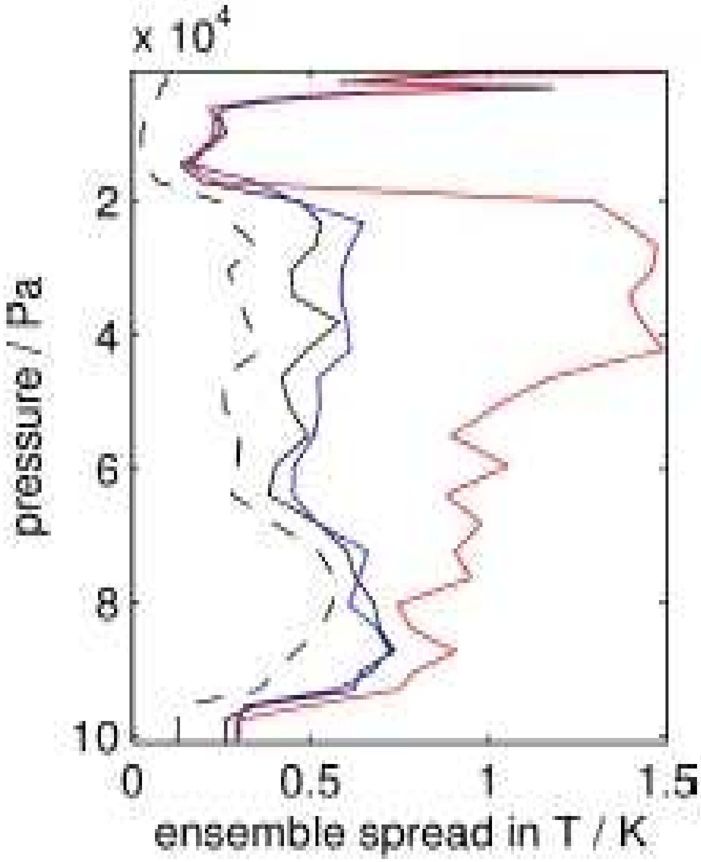
Predator-prey system with ~ 1000 individuals (McKane and Newman 2005)





- Accounting for discrete constituents leads to sustained oscillations with amplified internal variability
- Dramatic qualitative difference in response to internal and environmental/parameter noise

Example II: SCM mult. noise



- Apply mult. noise to parameterized $\partial_t T$ and $\partial_t q$
- SCM experiment of a TOGA-COARE case
- Dotted IC uncertainty; black MN; blue MN decorrelate each scheme; red MN decorrelate T and q perturbations
- Spread larger than with quenched random noise
- $C_p \Delta T = L \Delta q$ in phase changes matters

How far have we come in considering the physics of convective fluctuations?

An earlier workshop

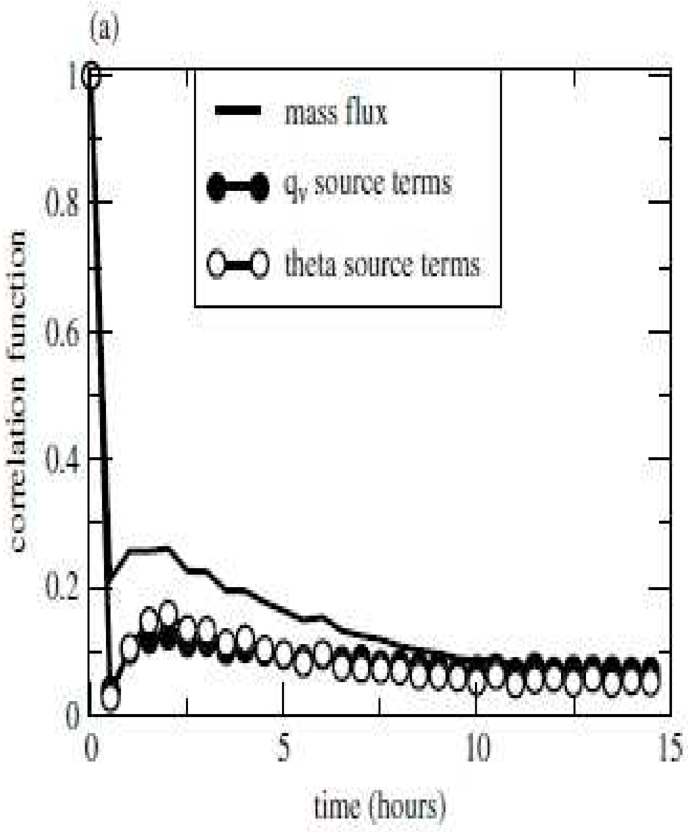
- ECMWF Workshop on Representation of Sub-grid Processes using Stochastic–Dynamic Models, 6-8 June 2005
- Working Group 1 Report: Issues in Convection

it is clear that a stochastic convection scheme is desirable

- Issues to be addressed...

Physical and numerical noise

Artificial noise



- Stiller (2009) N48L38 MetUM
- Convection schemes often shown artificial on-off behaviour

  even if subject to time-invariant forcing
- May need to remove artificial noise in order to see a physical source of fluctuations?

Scale-dependence of parameterization

Finite cloud number

- Convective instability is released in discrete events
- The number of clouds in a GCM grid-box is not large enough to produce a steady response to a steady forcing
- In equilibrium, for non-interacting clouds:
  - pdf of mass flux of a single cloud is exponential
  - number of clouds in finite-size region is given by Poisson distribution

    Craig and Cohen 2006
- Agrees well with CRM data

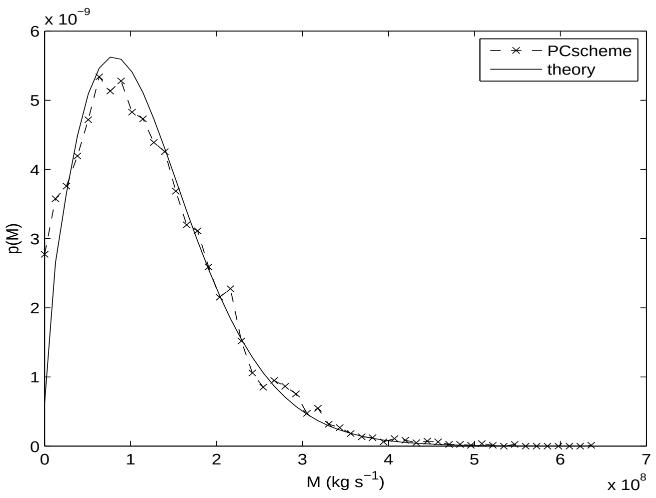
Plant and Craig parameterization

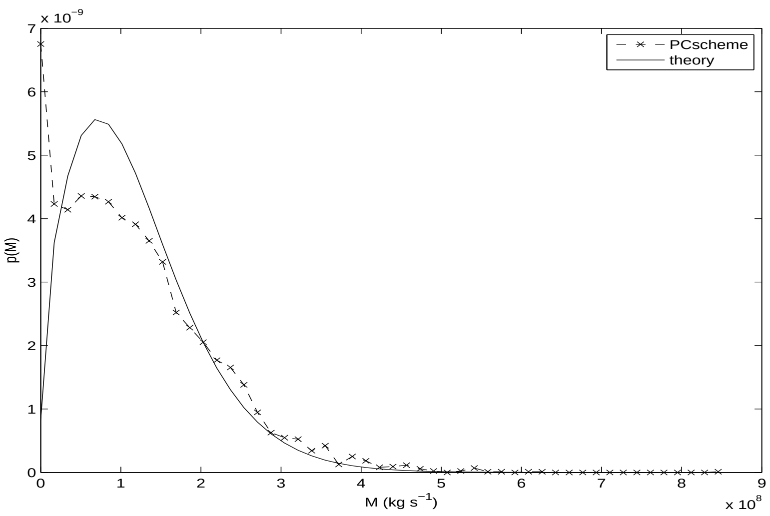
Mass-flux formalism...

1. average in the horizontal to determine the large-scale state
2. evaluate properties of equilibrium statistics: $\langle M \rangle$ and $\langle m \rangle$
3. draw randomly from the equilibrium pdf to get number and properties of cumulus elements in the grid box
4. compute convective tendencies from this set of cumulus elements

Grid scale $\neq$ large-scale state

- Idealized RCE on 3D domain with parameterized convection, $\Delta x = 32$km
- Reproduce theoretical pdf of mass flux by averaging input over $\sim (160)$km^2 for ~ 1hr
- But not if using grid-scale input





Prognostic closures

Prognostic closure

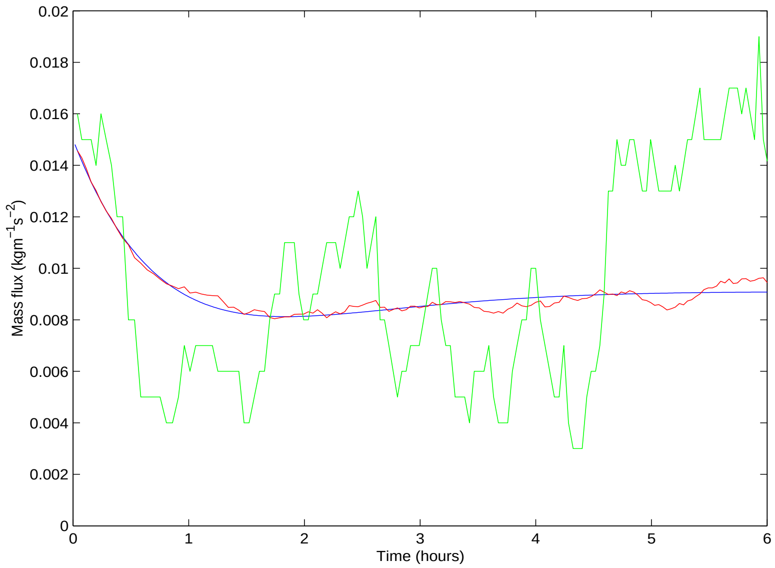
- Based on convective-energy-cycle equations

$$\frac{dA_i}{dt} = F_i - \gamma_{ij} M_j \quad ; \quad \frac{dK_i}{dt} = A_i M_i - \frac{K_i}{\tau_i} \quad ; K_i = \alpha_i M_i^2$$

- Recent revival of interest (Davies et al 2008, Wagner and Graf 2010, Yano and Plant 2011)
- Can construct stochastic form of these closures for a finite-size region using cellular automata with simple birth-death processes
- Point is that CA rules are strongly constrained by demanding that the ode's are recovered in the limit of infinite system size

Numerical example

Timeseries of M for Pan & Randall system, constant forcing with $\langle N \rangle = 10$ at equilibrium



Blue: solution of the Pan/Randall ODEs

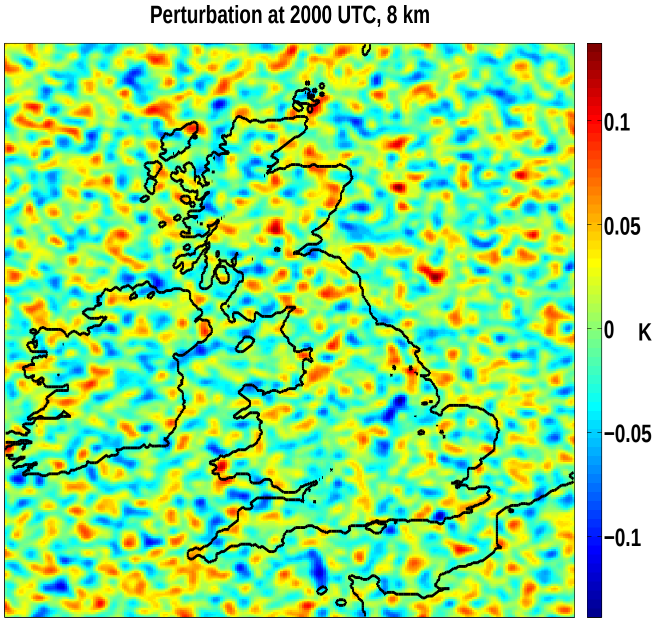
Green: a single realization of the stochastic CA

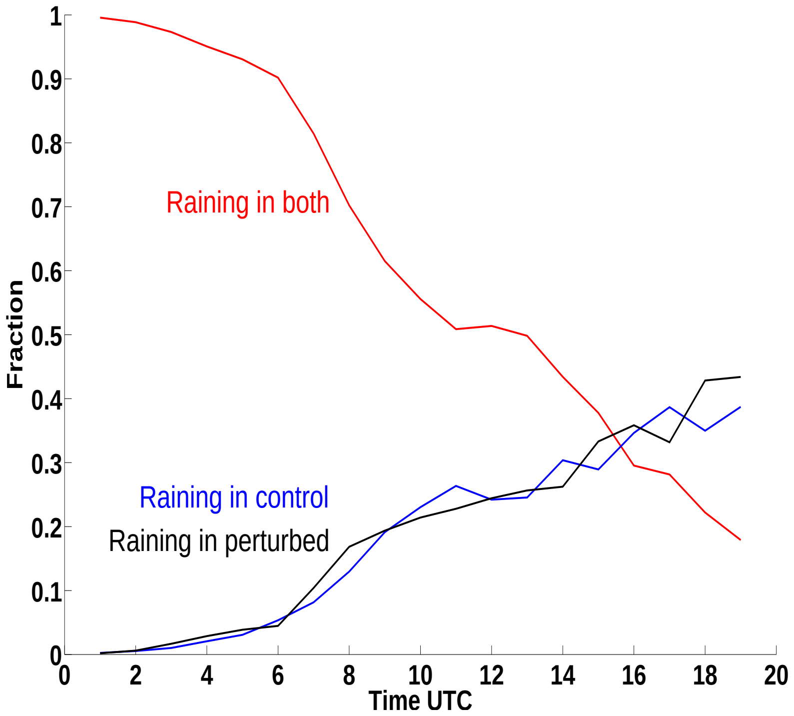
Red: ensemble mean of 100 realizations

Effects of sub-grid variability on initiation

Initiation

- Various demonstrations that boundary layer fluctuations can easily shift the locations of precipitating cells e.g. Leoncini et al (2010)





- Source of ensemble spread for convective-scale NWP

Accounting for fluctuations

- Bright and Mullen (2002) tried stochastic triggering function in Kain-Fritsch
- Recent attempts to try a closure of the form $\exp(-\mathrm{CIN}/\mathrm{TKE})$ emphasize role of boundary layer fluctuations, but not done stochastically (e.g. Hohenegger 2011)
- What is the correct coupling to the boundary-layer scheme?
- How does a closure based on boundary layer fluctuations behave in an equilbrium situation?

Propagation

Propagation

- We have difficulties with propagation and organization of convection, possibly because of lack of communication between cells
- Cellular-automata based approaches may be able to improve on this

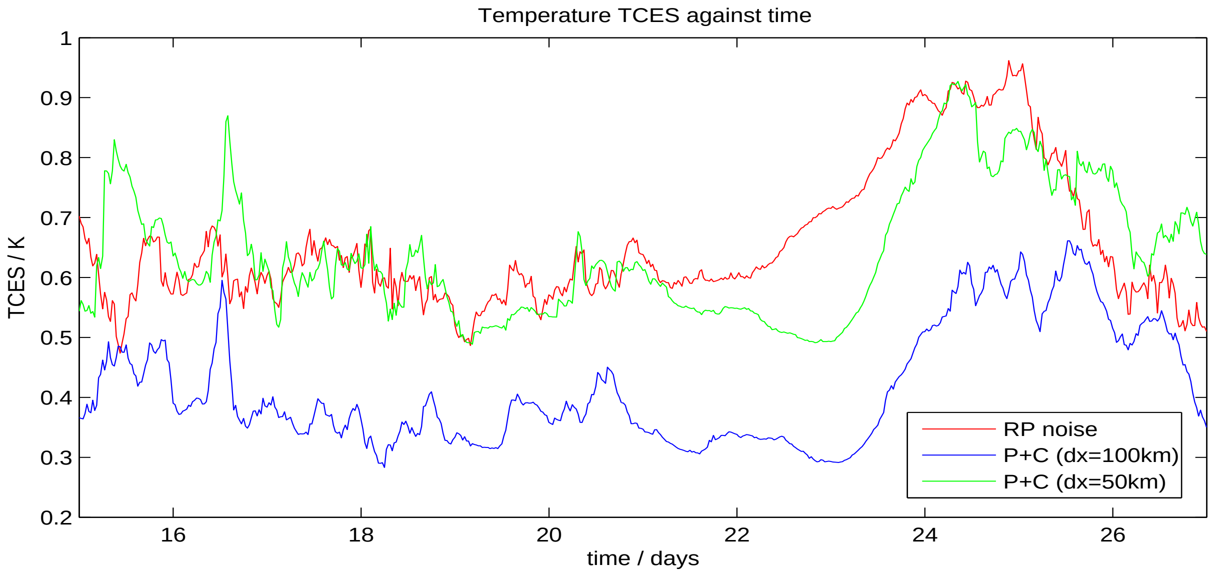
  Bengtsson-Sedlar talk later...
- Grandpeix and Lafore (2010) propose simple coldpool propagation model but only applied in 1D
- Not necessarily stochastic!

Summary

- Many uncertainties (structural, parameter, intrinsic) associated with convection
- Discrete nature of cumulus clouds seems to demand a stochastic approach
- Fluctuations increase as Δx reduces, and must depend on Δx and intensity
- We know how to account for this in equilibrium
  - But note that number fluctuations of $= 2/\sqrt{N}$ implies a spectral not bulk formulation
- We could do this out-of-equilibrium
- Far from equilbrium situations need careful coupling of convective and boundary-layer schemes

Sampling uncertainty

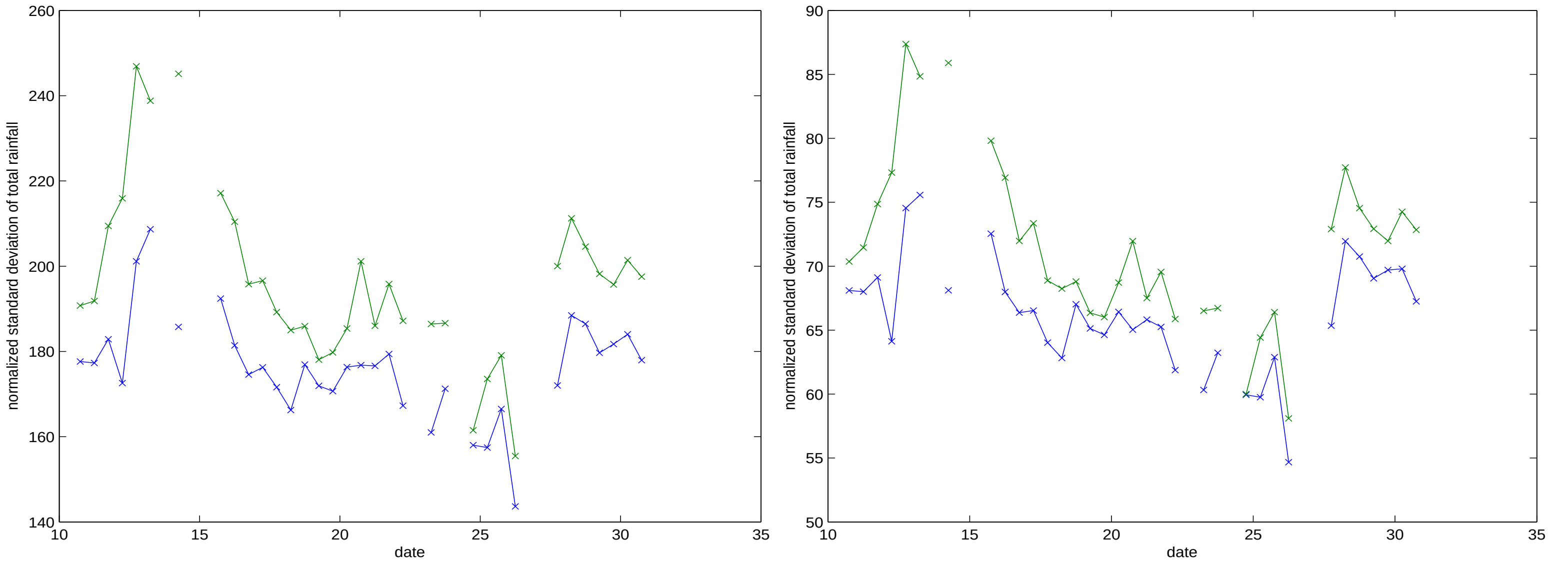
- Spread in column-average T from Plant-Craig scheme as function of grid-box size



Similar to mult. noise or random parameters for $\Delta x = 50\text{km}$

MOGREPS trial

- Running at $\Delta x = 24$km in MOGREPS ensemble



Std. dev. in rainfall averaged over $(48\text{km})^2$ (left) and $(120\text{km})^2$ (right)