Stochastic aspects of convection-permitting models

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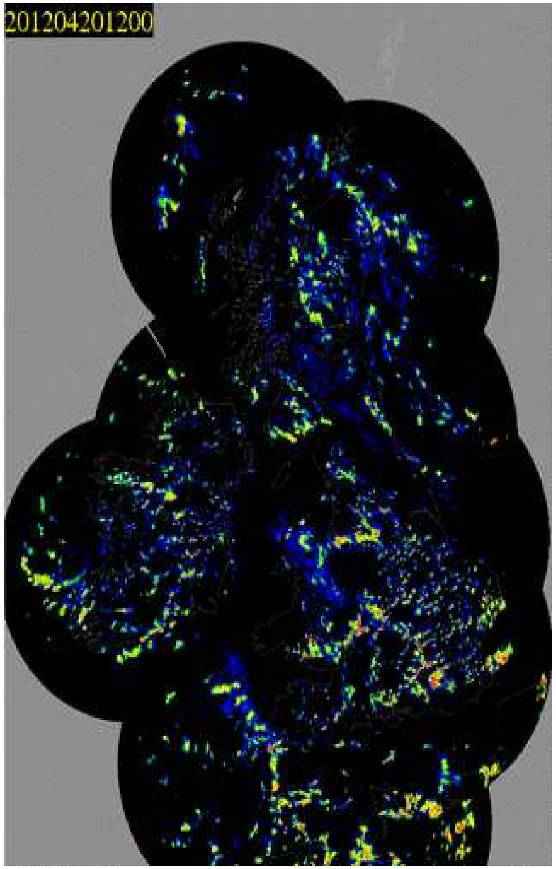
Model filter

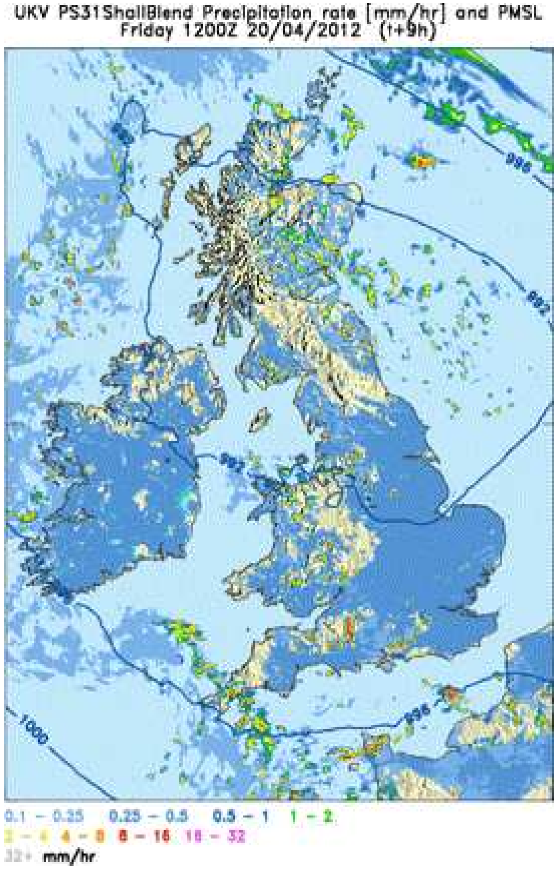
- A numerical model of the atmosphere is based on a filter separating the flow into resolved and unresolved parts
- The purpose of parameterization is to feedback effects of the unresolved processes on the resolved state
- In general:
  - the feedback will depend on the nature of the filter
  - the feedback will not be a known deterministic function of the resolved state
- An ensemble-mean filter is deterministic
- A space/time filter might be approximated by sampling from possible physical realizations of the feedback from some conditional pdf

Ensemble mean parameterization

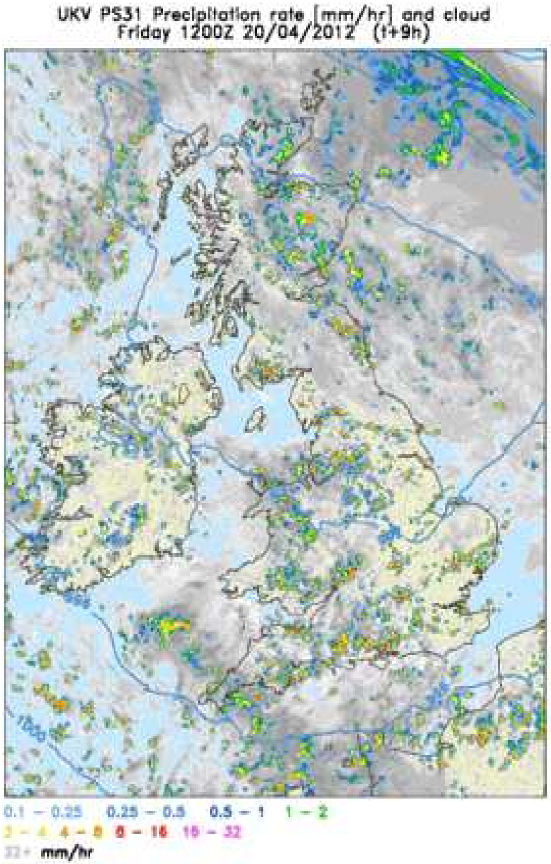
Example case of scattered showers over UK



Radar image



1.5km parameterized



1.5km explicit

(example from Adrian Lock)

The grey zone

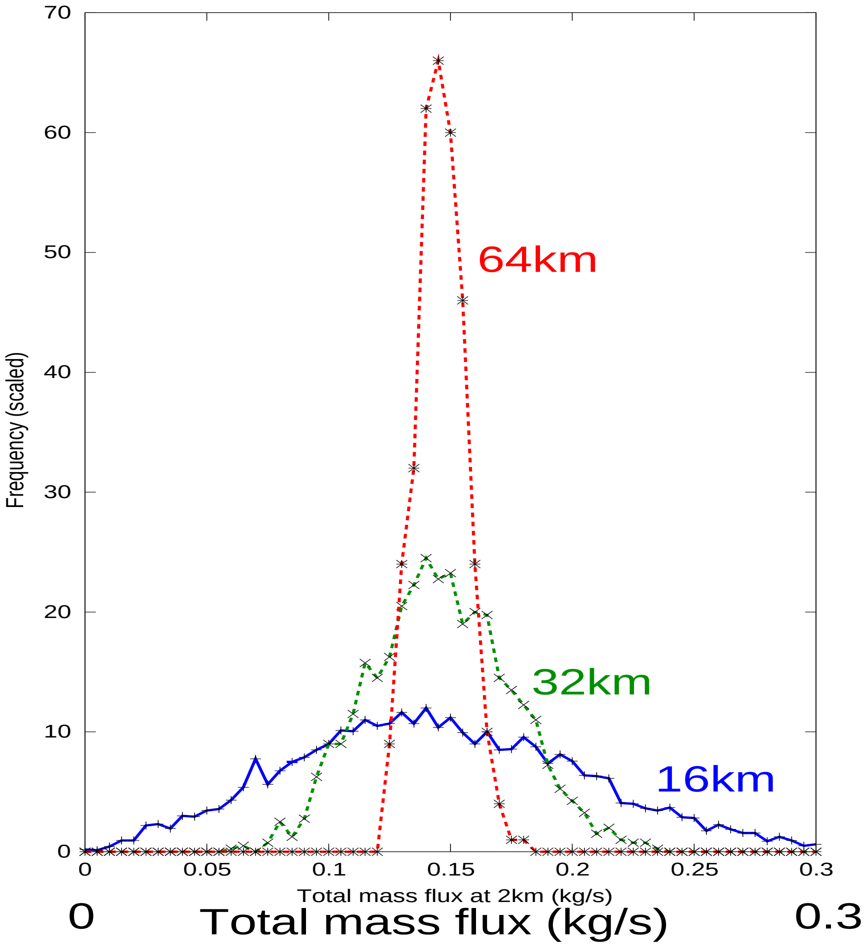
- For phenomenon of scale l and for Δ a filter lengthscale...
    - if $l \gg \Delta$ the phenomenon is well resolved
    - if $l \ll \Delta$ the phenomenon is fully parameterized
    - if $l \sim \Delta$ then the representation of the phenomenon is sensitive to details of the filter
- A spatially-averaged field on the scale Δ may look turbulent but an ensemble-averaged field on that scale looks smooth
- What do we want our high-resolution models to produce?
    - a more detailed picture of the ensemble-mean flow?
    - a particular, possible realization of the actual flow?

Stochastic effects, reducing Δ

- GCMs have difficulties with organized convective structures where relevant interactions span a range of scales straddling Δ
  - talks by Khouider and Shutts

- For smaller $\Delta \sim$ cloud spacing, then even scattered convection becomes stochastic because few clouds $\Rightarrow$ poor sampling of the full pdf of possibilities

Range of convective states

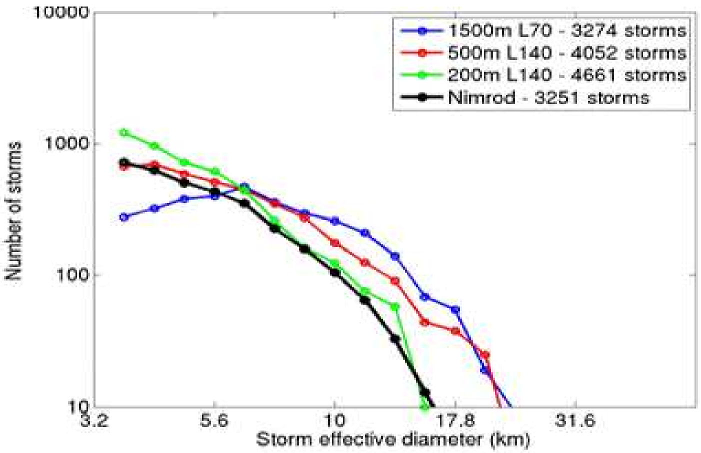


(Plant and Craig, 2008)

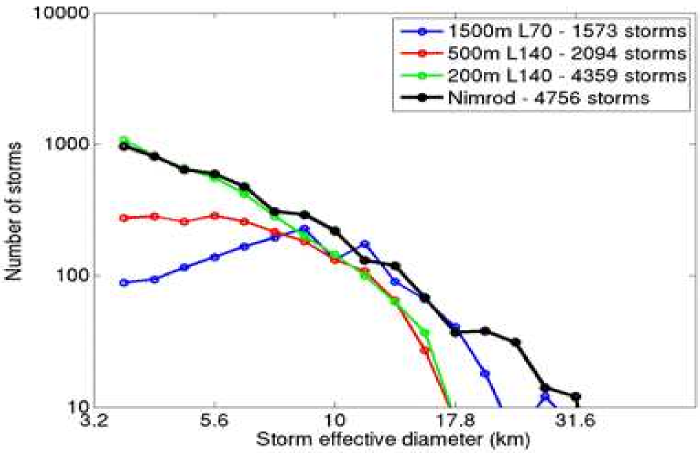
Distribution of mass fluxes in equilibrium convection over ocean. Averaged over various areas.

Convection-permitting models

- If $\Delta \sim$ convective storm size, normal practice is to switch off deep convection parameterization
- Dynamical treatment of cloud assumed better than parameterized treatment
- Dynamics will be sensitive to details of filter, inc. grid length, numerics



Weak showers case



Deep convection case

(Hanley et al 2015)

Stochastic effects, reducing Δ

Uncertainties remain in the representation of deep convection that may be usefully addressed with stochastic approaches

- Shallow convection may be in a regime where $\Delta \sim$ cloud separation
  - talk by Seifert
- Initiation of dynamically-simulated deep convective clouds will depend on the state of the turbulent boundary layer

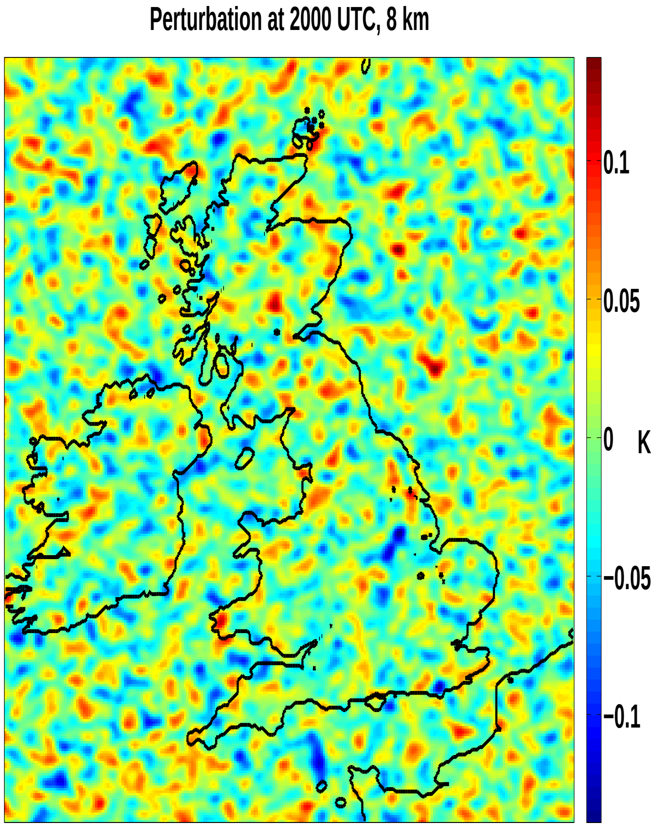
Turbulence parameterization

- Our turbulence parameterization is formulated as an ensemble average
- Spatial-mean boundary-layer tendencies will vary randomly about that unless eddy size $\not\ll \Delta$
- Largest, most vigorous eddies are responsible for initiating convective clouds and have size $\sim h \sim$ cloud size $\sim \Delta$
- $\Rightarrow$ at just those Δ where we might switch convection parameterization off, the boundary layer turbulence enters a grey zone where large eddies are poorly sampled by spatial averaging

- We need to contemplate a stochastic representation of the boundary layer

Gaussian bumps

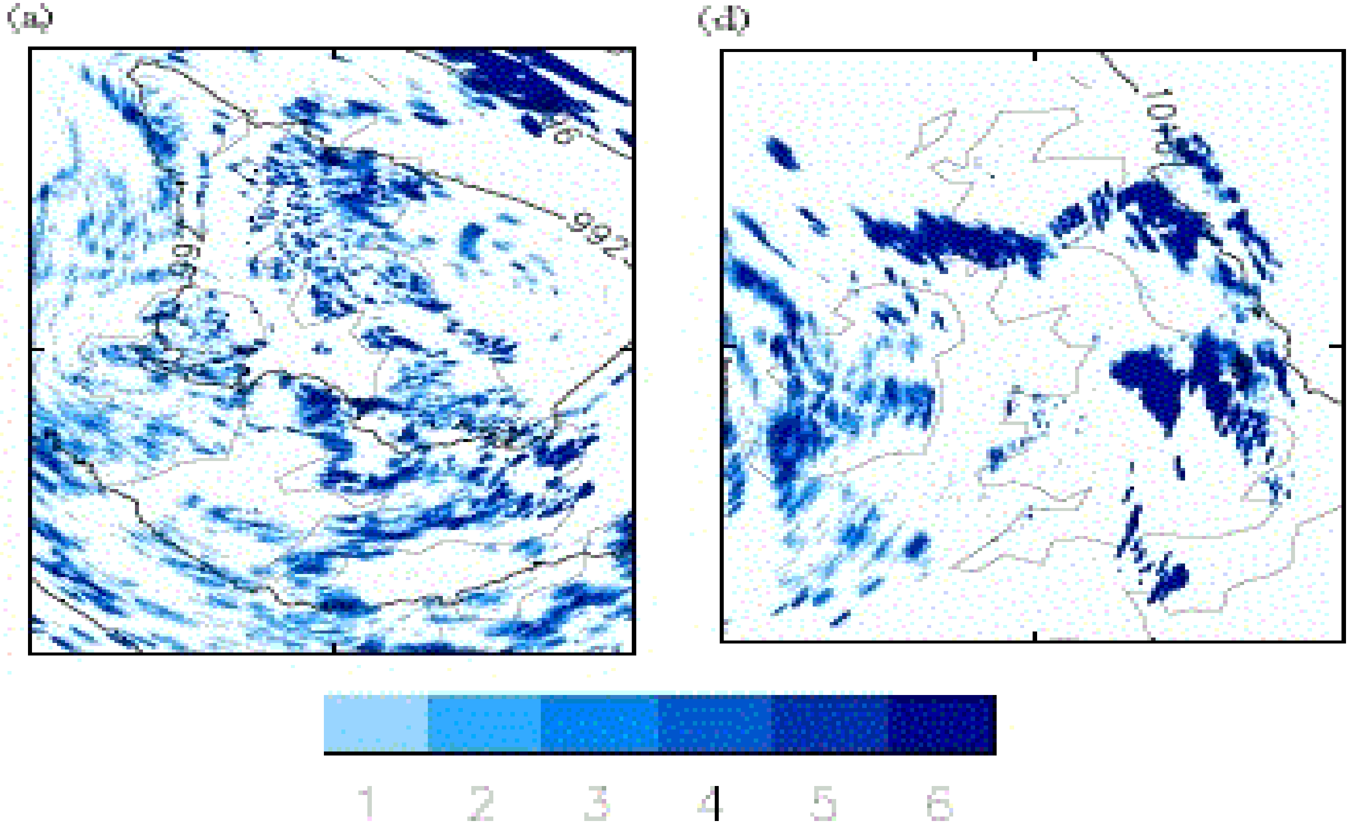
- Superposition of 2D Gaussian kernels applied to random number for each grid location, $\sigma_x \sim 10$ km
- Applied to potential temperature at a level within the boundary layer
- Every 30 min
- Small fluctuations ~ 0.1K
- Cautious approach used in predictability studies



(e.g. Leoncini et al 2010, 2013)

Impact of Gaussian bumps

Number of ensemble members that are raining:

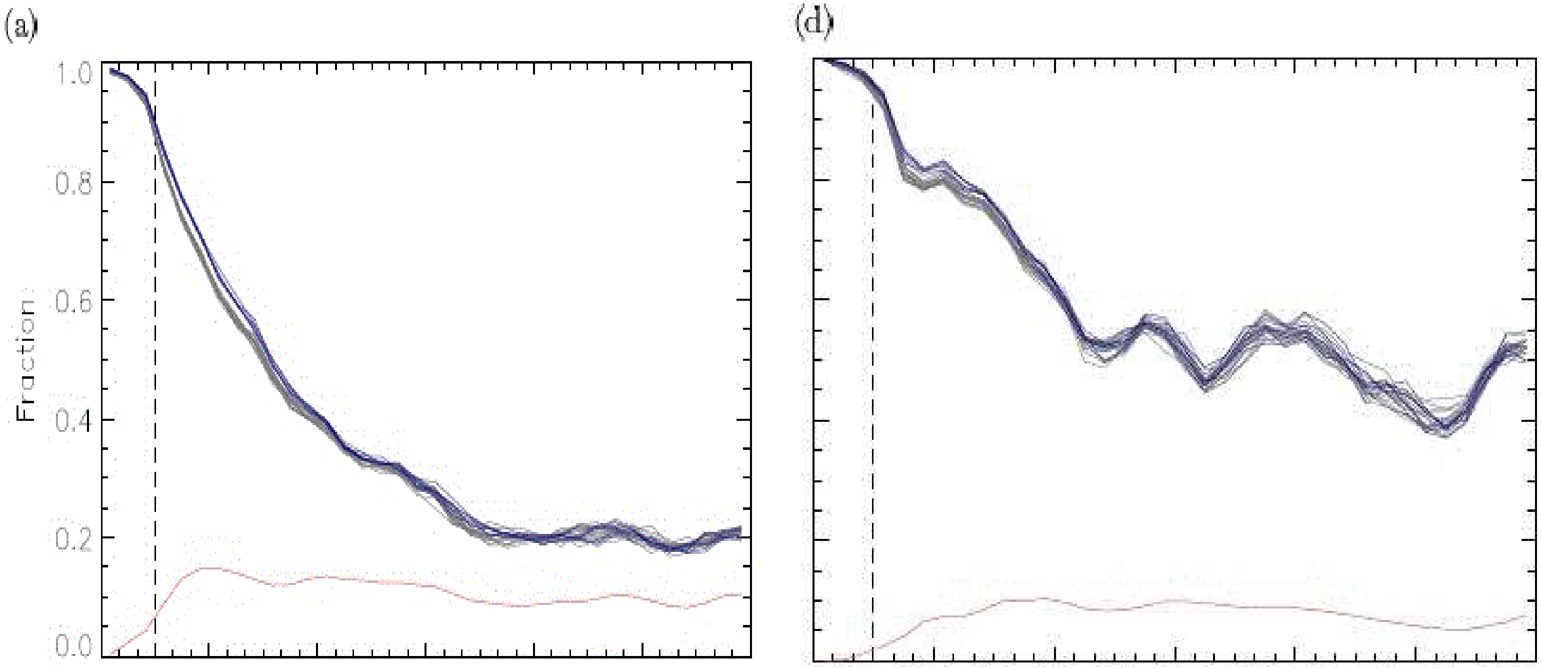


Small perturbations can easily shift the locations of precipitating cells in some cases

(Flack et al 2017)

Displacement of Convection

Fraction of points that are raining in both of a pair of simulations



Equilibrium convection Non-equilibrium

Equilibrium case saturates at 20% after $\sim$ 20 h, compared to 10% for completely random scatter through model domain

Implications I

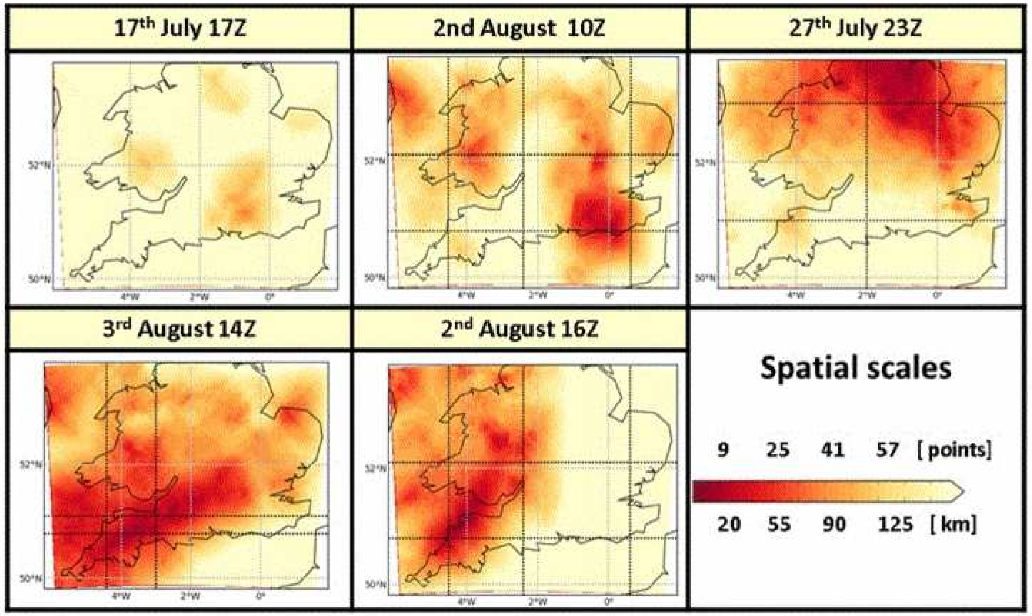
Testing changes to effects of other model settings needs to be done in an ensemble context.

	CDNC×2	CDNC×4
More rain	12	6
Less rain	24	30

Example of 6-member case study with enhanced cloud-doplet number concentration

Implications II

Need to evaluate simulations against observations with more suitable metrics than point-to-point comparisons



e.g., spatial neighbourhood approaches that ask how much we have to coarse-grain the precipitation data to get agreement between two fields

(Dey et al 2016)

Summary of Gaussian bumps

- Application can be anywhere in boundary layer
- Time/space correlations of modest effects only
- Amplitude of buoyancy perturbations applied is most important sensitivity
- Perturbations produce earlier initiation (may be a major motivation for their introduction)
- Dynamics of convective cells largely unchanged: may be displaced and *could* increase number

BL scaling

The turbulent boundary layer under deep convective storms is itself primarily buoyancy driven and its variability can be well described by scaling parameters:

Length scale	h
Velocity scale	$w_* = \left(\frac{ghH}{\rho c_p \theta_0}\right)^{1/3}$
Timescale	$t_* = h/w_*$
Temperature scale	$\theta_* = \frac{H}{\rho c_p w_*}$

for h the depth of the layer and H the surface heat flux

Towards stochastic parameterization

- Lock in current 1.5km MetUM operational model:
    - adds perturbations $\sim \theta_*$ with uniformly distributed random numbers
- Kober and Craig (2016) in 2.8km COSMO tests:
    - adds perturbations $\sim \sqrt{\overline{\theta'^2}}$ and Gaussian bump style random number structure

Limited number of large eddies

- Assume key source of variability is due to finite number of large eddies n averaged over in a given area
- The large eddies are independent and so Poisson
- Heating from each event warms area of $\sim h^2$ by amount $\sim \theta_*$ in time t_*

$$\left.\frac{\partial\theta}{\partial t}\right|_{\mathrm{BL}} = \frac{n}{\overline{n}} \left.\frac{\partial\theta}{\partial t}\right|_{\mathrm{det}} \qquad ; \qquad \overline{n} = \frac{\Delta x \Delta y \Delta t}{h^2 t_*}$$

Very shortly to be tested in MetUM (Clark et al)

Summary

- Spatial averaging $\neq$ ensemble averaging for $l \sim \Delta$
- If spatial average wanted, an important source of variability arises if the parameterized phenomenon includes important dynamical modes not much below the filter scale
- This occurs in convective parameterization context (“not enough clouds in the grid box”)
- It also occurs in convection-permitting models in respect of the parameterized BL turbulence
- Simple stochastic noise can systematically affect initiation of deep convective clouds in such models
- Schemes now being explored that can account for turbulent variability and filter size Δ in a natural way

References

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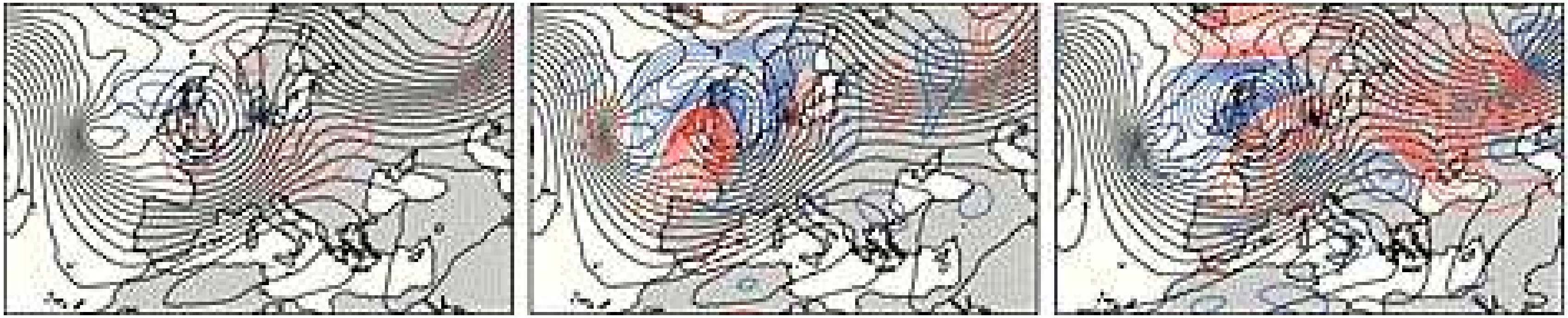
Extras: if time and interest

Upscaling of perturbations

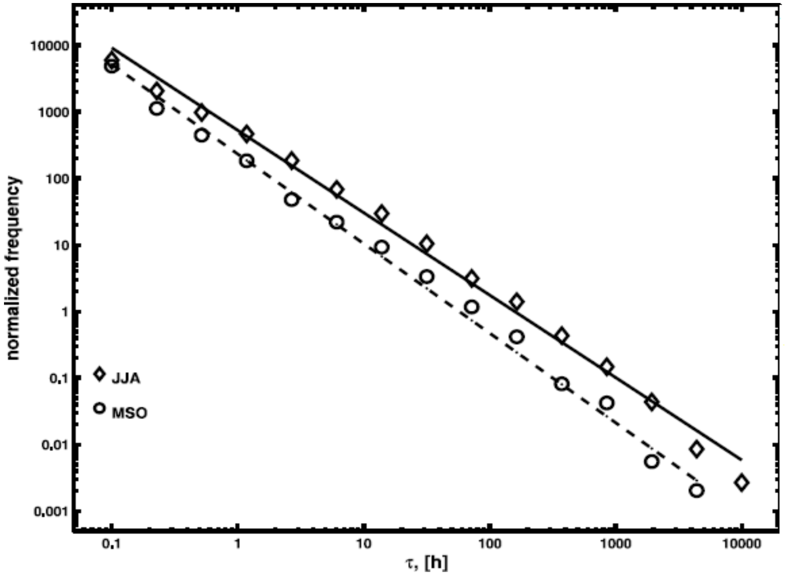
- One-off stochastic boundary-layer perturbation after 15 h, produces 500 hPa geopential simulations synoptic scale in 2.8 km large-domain COSMO simulation (right).



- Stochastic convection scheme in 28 km model is effective in capturing this upscale growth (centre, Plant-Craig).
- Deterministic scheme has very weak response (right, Tiedtke) as intended for an ensemble-mean parameterization method

Convective regime frequencies

Timescale, $\tau_c = CAPE/(dCAPE/dt$ due to convection)



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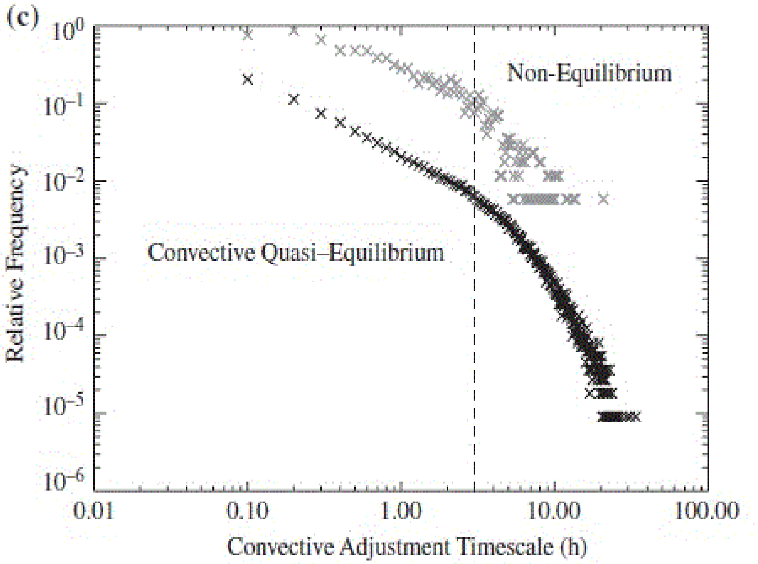

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(Zimmer et al 2011; Flack et al 2016)