What (if any) constraints are desirable on near grid-scale noise?

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With thanks to: G. Leoncini, M. Ball

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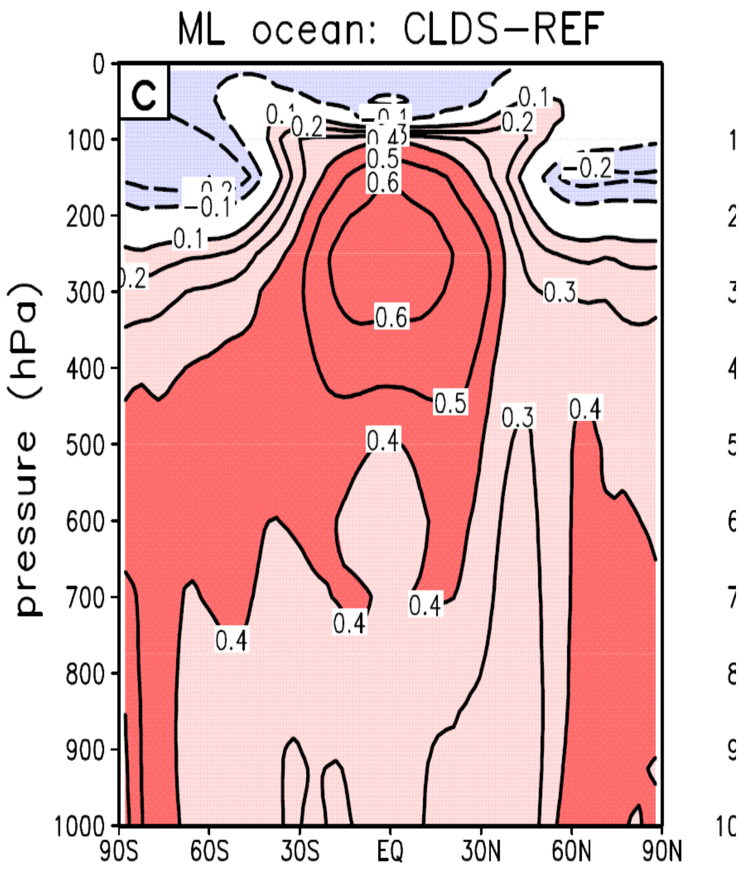
Mathematical Challenges in Climate Science, Lorentz Centre

Example



- MCICA is radiation scheme that attempts to deal well with cloud-radiation interactions
- A reasonable GCM implementation has random errors
- Stochastic drift in mean climate, similar to small increase in solar constant (Raisanen et al. 2005)

Outline

- Some general aspects of parameterization
- Physical constraints on near-grid scale noise?
- Some example schemes
- Do the constraints matter? A few results
- Closing remarks

Some general aspects of parameterization

Relevant scales

At least 3 important scales to consider in parameterization:

1. intrinsic scale of the process to be parameterized
   (turbulent eddy sizes, cloud dimensions or separations...)
2. a large-scale, sufficient to contain many instances of the process
   i.e., scale at which time average $\approx$ space average $\approx$ ensemble average
3. the model grid box size

The cumulus ensemble

The Arakawa and Schubert (1974) picture

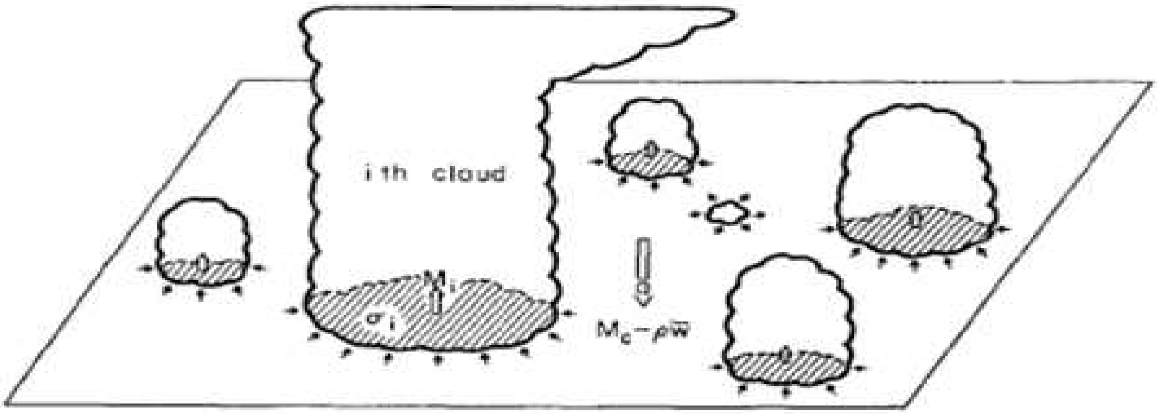


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

- Convection characterised by ensemble of cumulus clouds
- Scale separation in both space and time between cloud-scale and the large-scale

Relevant scales

1. intrinsic scales
2. large-scale
3. model grid box

Important note: Will assume that (2) exists in practice, and is well-separated from (1)
i.e., the statistics of the parameterized process are a function of large-scale state

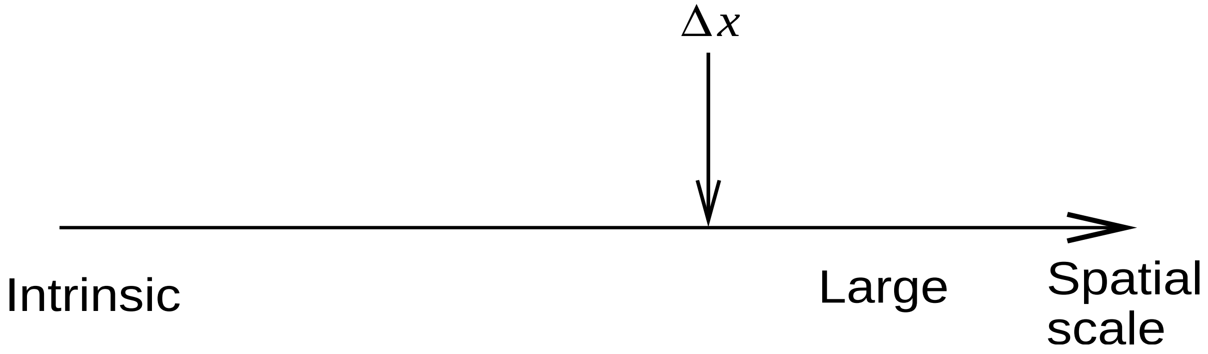
Relevant scales

1. intrinsic scales
2. large-scale
3. model grid box

Important note: Will focus on spatial scales from now on, but very similar arguments apply to the time scales

Parameterization strategy

Is a function of the grid scale



- Determinstic parameterization
- Fluctuations small on scale Δx
- Parameterized process is a function of current state of grid box

Parameterization strategy

Is a function of the grid scale

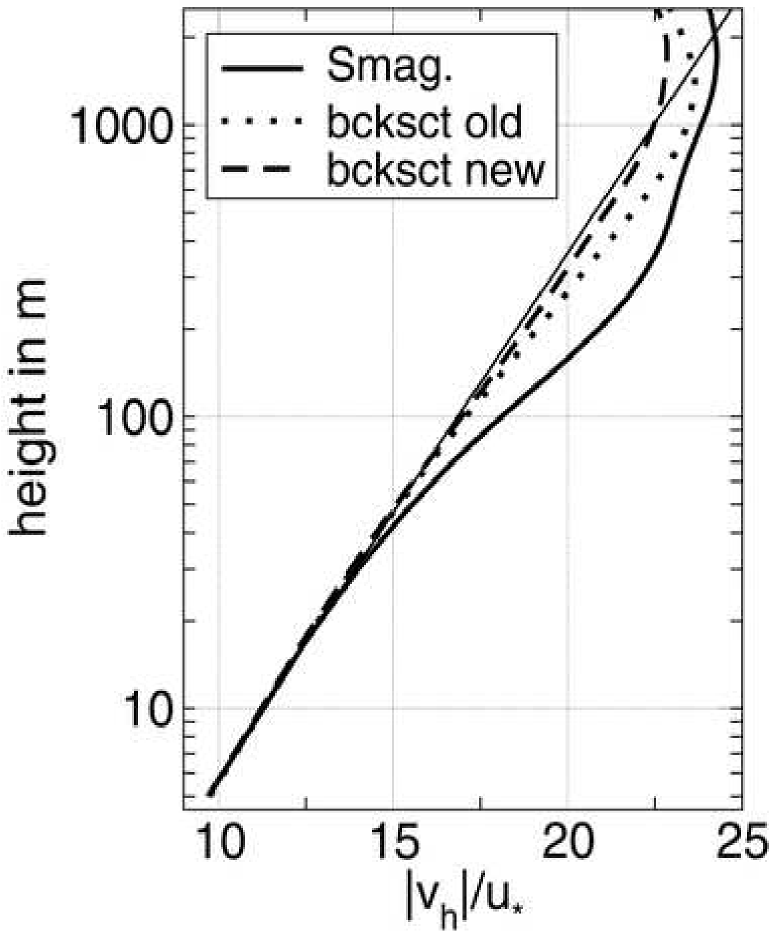
- Stochastic parameterization
- Parameterized process is a function of large-scale state
- Grid-box state $\neq$ large-scale state
  space average over $\Delta x \neq$ ensemble average
- Process as realized on grid-box scale is a sub-sampling of the full ensemble so fluctuations important

Parameterization strategy

Is a function of the grid scale

- Process is resolved (partially!)
- Difficult to model in a systematic way
- But noise may be helpful in some ways

Stochastic Backscatter



- LES of dry, neutral boundary layer
- Close to surface, size of dominant eddies $\sim \Delta x$
- Improved shear near boundaries with stochastic backscatter energy to grid
- Plot for $\Delta x = 100$m, $\Delta z = 10$ to 50m (Weinbrecht and Mason 2008)

Relevant scales

1. intrinsic scales
2. large-scale
3. model grid box

Important note: **None** of these scales are necessarily fixed in a simulation!

Implications

The ideal parameterization would

- Know what the three scales are
- Adjust its strategy (become stochastic, switch-off) appropriately

In particular:

- If in stochastic mode, the sub-sampling depends on all three scales
- Stochastic aspect will depend on Δx
- Need large-scale state from suitable averaging over the grid

Physical constraints on near-grid scale noise?

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Impact of stochasticity

- Stochastic aspect will introduce near-grid scale noise
- The noise may have a complicated character, which is dictated by our model (deliberate or otherwise!) of the stochastic process

  thresholds will often result in noise
- May be important through stochastic drift, noise-induced transitions etc

That's not noise, that's music

(Feynman)

A practical view

- Near-grid scale in model is not energetic enough
- Adding near-grid scale noise can correct that
- Some very simple noise generators are beneficial

Buizza et al. 1999, Hou et al. 2001, Bright and Mullen 2002...

So...

Does it matter what tune we play, or should we just make a suitably loud noise?

In other words...

Is it useful to impose physical constraints on the added noise, and if so then what constraints are useful?

Which stochastic parameterization?

Evolution of model state X given by

$$\partial_t X = D(X) + P(p, X)$$

$D =$dynamics, $P =$parameterized physics, $p =$the parameters

- Various types of scheme imply various physical constraints on the noise
- Which works best for a given problem?
- Can (and how should?) various beneficial schemes be combined?

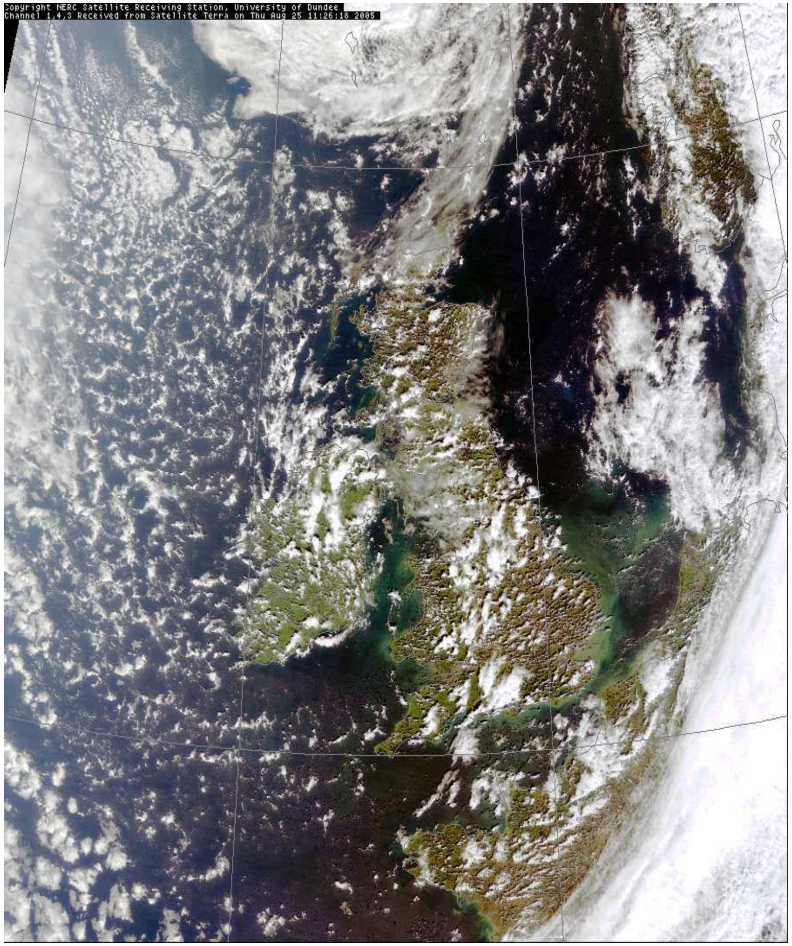
Additive noise

$$\partial_t X = D(X) + P(p, X) + \varepsilon$$

Additive noise, possibly with no constraints

e.g. Done et al. 2008

...can be good enough

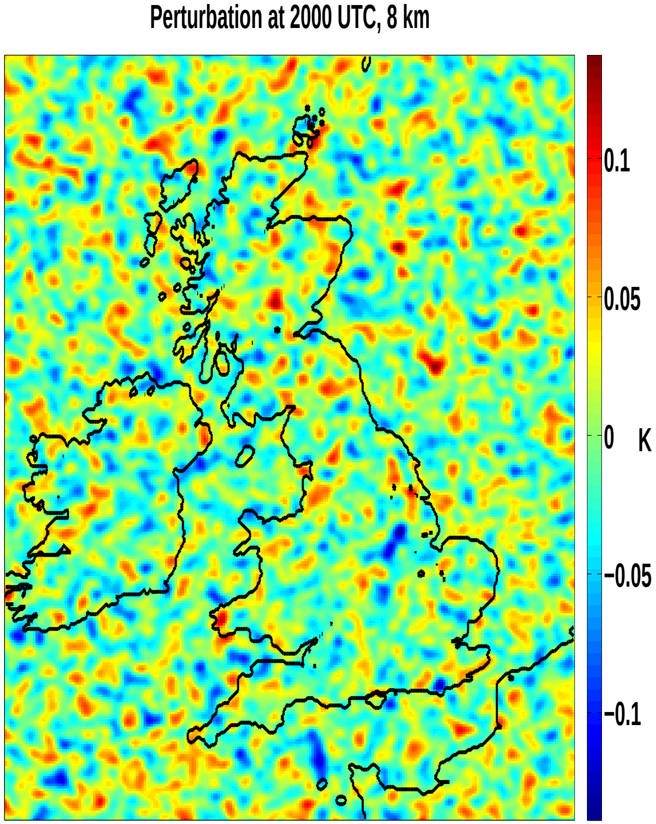


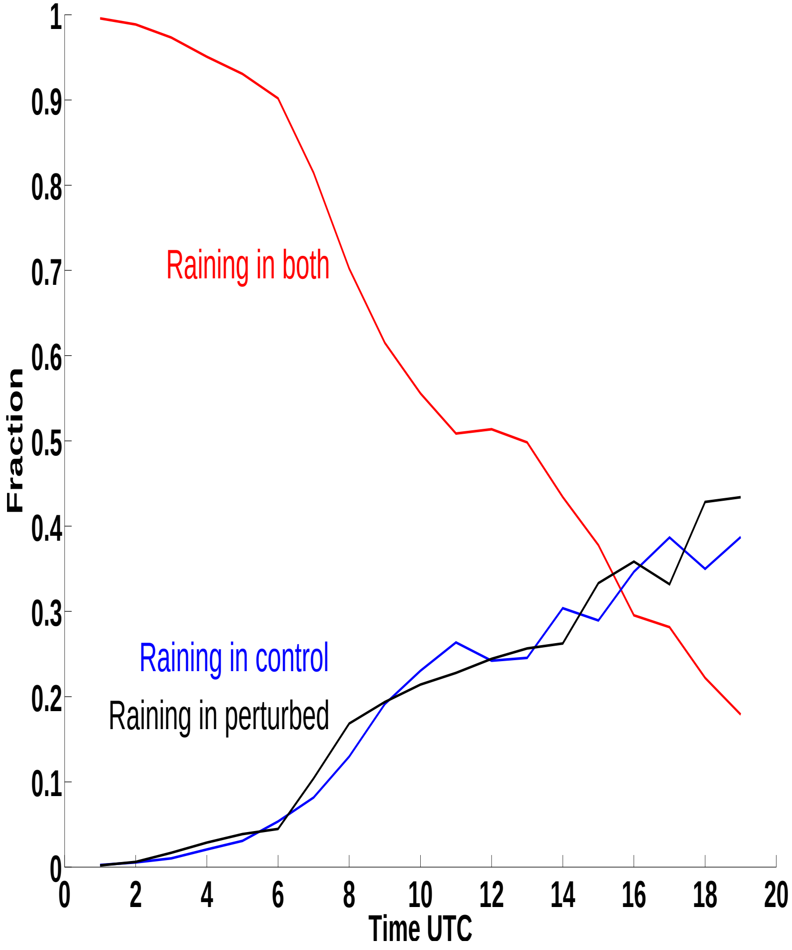
- Case from CSIP IOP18
- Scattered convection over S. England
- 4km simulation, partially-resolved convection
- Model produces scattered clouds, but they might be scattered in many different ways

Leoncini et al. 2009

...can be good enough

Perturbations to boundary-layer θ, applied every 30min





Multiplicative noise

$$\partial_t X = D(X) + \varepsilon P(p, X)$$

Multiplicative noise: constraints imposed are dictated by the determinstic parameterizations

e.g. Buizza et al. 1999

- imposes a vertical structure
- imposes correlations between variables
- e.g., multiplicative noise for convection would express uncertainty about its strength, but not its existence or its character

Parameter noise

$$\partial_t X = D(X) + P(p_\varepsilon, X)$$

Parameter uncertainty: constraints imposed are dictated by the structure of the determinstic parameterizations

e.g. Arribas 2004

- e.g., our model of the convective plume is sound, but uncertain about entrainment

Input-state noise

$$\partial_t X = D(X) + P(p, X_\varepsilon)$$

Input-state uncertainty: constraints imposed by the range of admissible atmospheric states

e.g. Tompkins and Berner 2007

- Parameterized process acts only over part of the sub-grid area, for which X is not a good representation
- Hard to control and not easy to specify X_ε
- But this is effectively happening anyway in many stochastic implementations!

  (Consider sequential physics with a single scheme being stochastic)

Truly-stochastic scheme

$$\partial_t X = D(X) + P_\varepsilon(p, X)$$

Parameterization explicitly designed to be stochastic, following the conceptual framework presented earlier

e.g. talks this week

- Conceptually satisfactory, but much effort, which may not be needed?

Specific examples of schemes

Multiplicative noise

Buizza et al. 1999, and used successfully at ECMWF

$$\partial_t X = D(X) + \varepsilon P(p, X)$$

- Tendencies to T, q, u and v rescaled
- Scaling at end of timestep, so applied to sum of all parameterizations
- ε uniformly distributed from 0.5 to 1.5
- ε held fixed within 10° areas and for 6h

Plant and Craig parameterization

- A P_ε scheme for deep convection
- Number of cumulus clouds $\langle N \rangle$ in GCM grid box need not be large
- Uses mass-flux formalism with spectrum of plumes of varying sizes

  (In the Arakawa and Schubert tradition)
- Selects a random sample of such plumes
- Stochastic part of $\partial_t X \sim \sqrt{\langle N \rangle}$
- cf. multiplicative noise in which it $\sim \langle N \rangle$

Plant and Craig parameterization

Enacts the conceptual framework presented earlier:

1. Average in the horizontal and over time to determine large-scale state
2. Evaluate properties of large-scale equilibrium statistics
3. Sample randomly from the equilibrium pdf to get the number and the properties of the plumes in the grid box
4. Compute convective tendencies from this set of cumulus elements

Some details

- Ensemble-mean grid-box mass flux $\langle M \rangle$ from CAPE closure
- Distribution of mass flux across spectrum from Craig and Cohen (2006) theory of non-interacting plumes
- Each plume based on modified Kain-Fritsch entraining/detraining plume model

Do the constraints matter?

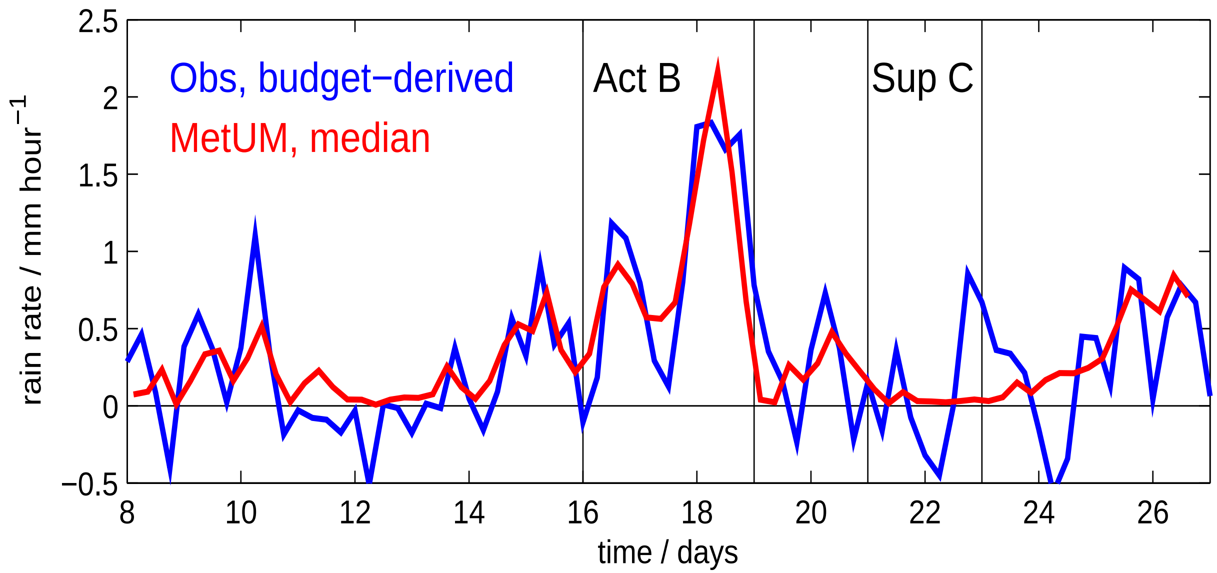
Framework of tests

Single-column tests of GCSS, PCCS, case 5

- Using MetUM version 6.1
- No dynamics feedback
  (tests underway for aqua-planet)
- 39-member ensembles used
- small initial condition perturbations to boundary-layer temperature
- different random number seed for the stochastic method in each run

GCSS Case 5 Test

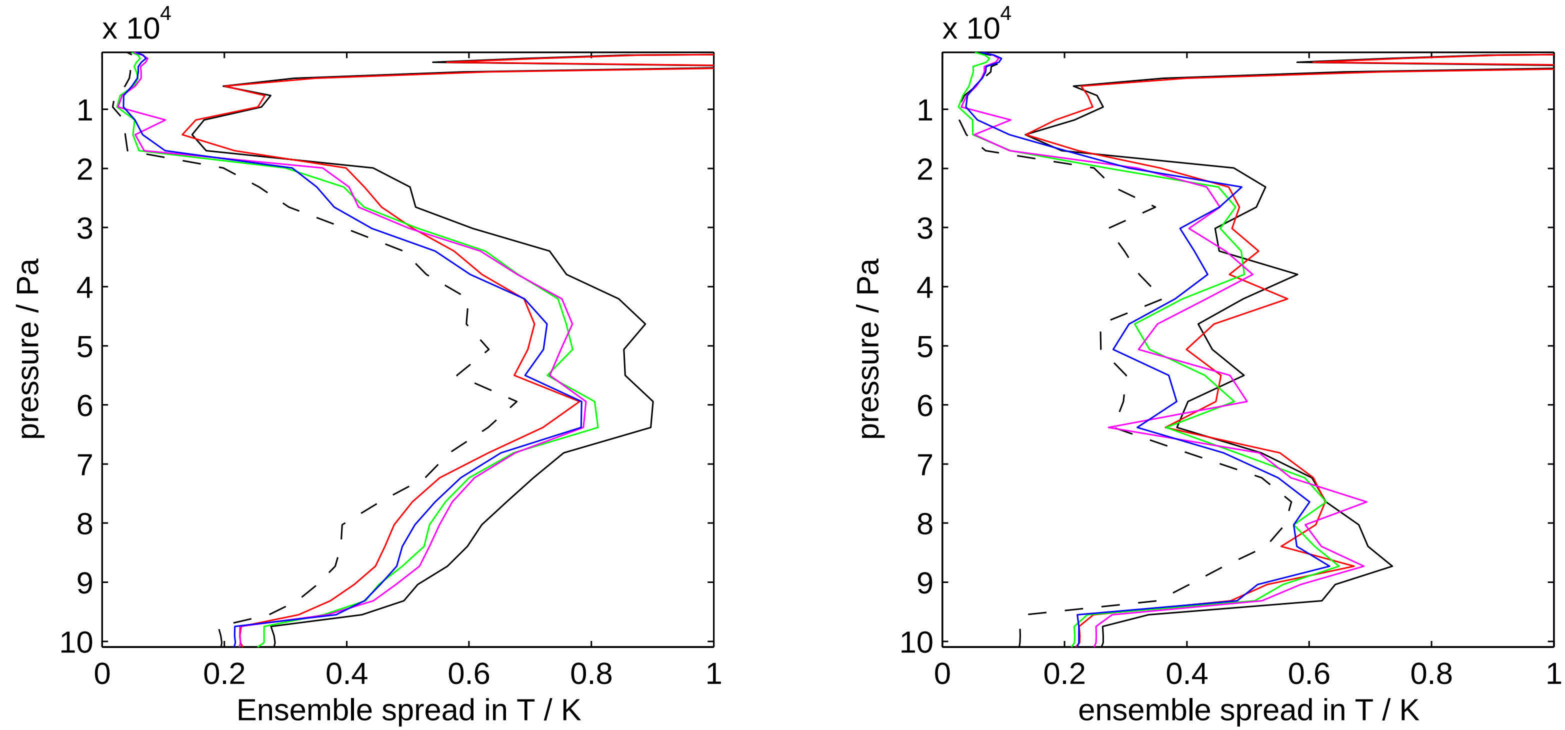
- Case is for tropical west-pacific warm pool, 9th-28th January, 2°S, 156°E
- Forcing data derived from TOGA-COARE



Rainfall variation due to mid-tropospheric moistening/drying by imposed dynamical tendencies

Test 1

- Apply multiplicative noise to one scheme only
- Active (left) and suppressed (right) phases



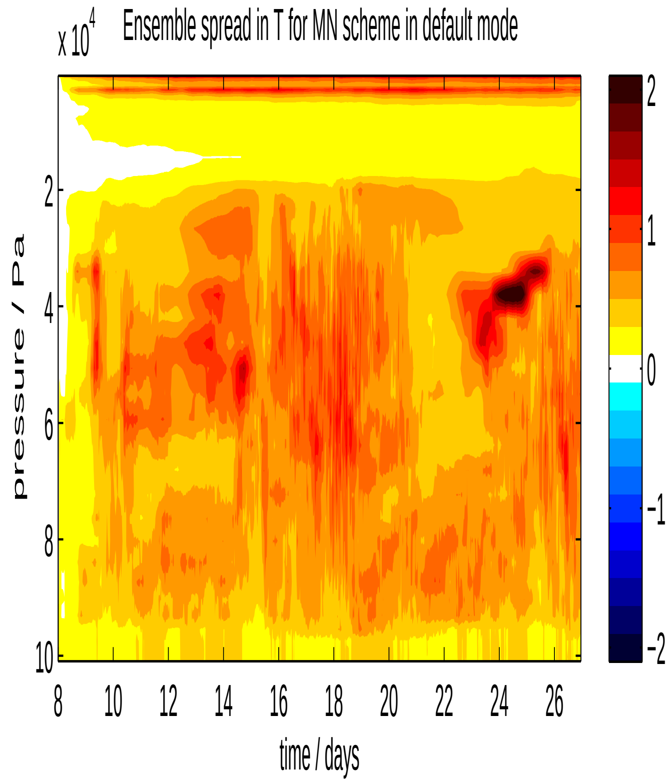
Dotted: IC, Black: all, Red: radiation, Green: boundary layer, Purple: convection, Blue: large-scale cloud

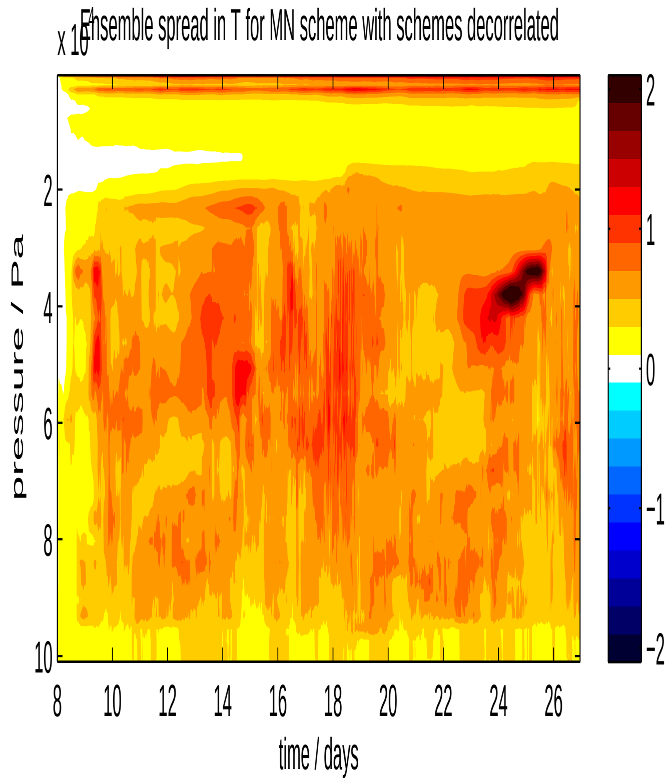
Test 1

- Perturbing radiation scheme produces large, unrealistic, spread in stratosphere
- Similar vertical profiles of spread
  (convection scheme responds to any tropospheric perturbation)
- Spread from perturbing any one scheme $\sim 1/2$ spread from 4 schemes together

Test 2

- Decorrelate multiplicative noise to each scheme

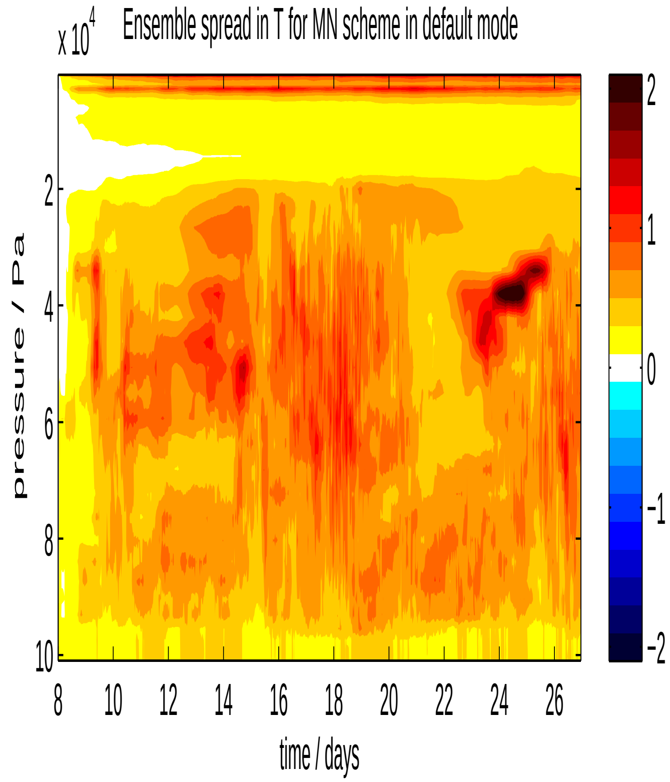


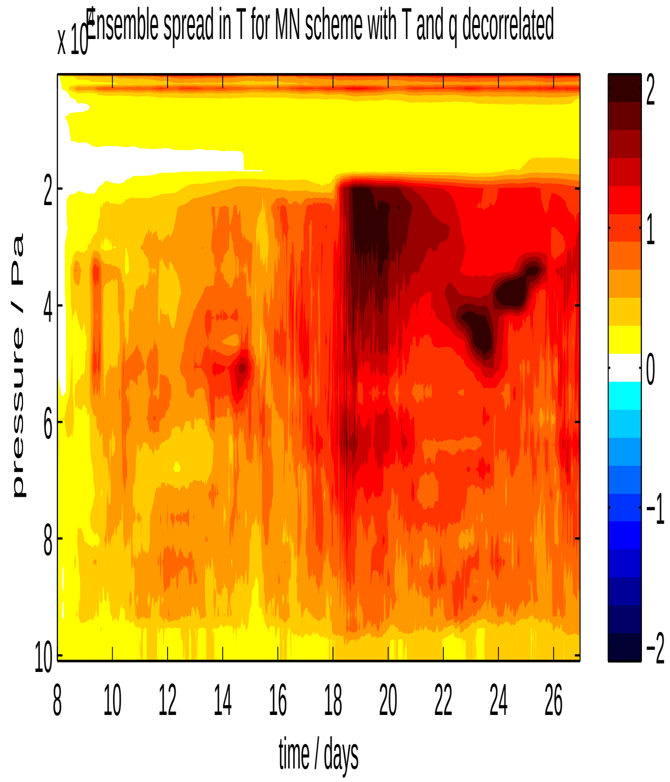


Differences are small

Test 3

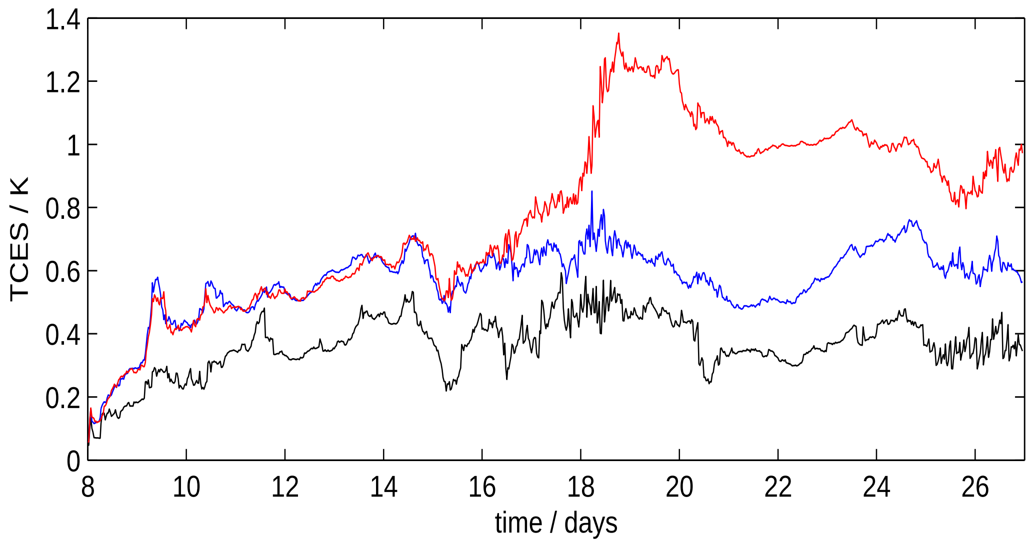
- Decorrelate multiplicative noise to $\partial_t T$ and $\partial_t q$





Test 3

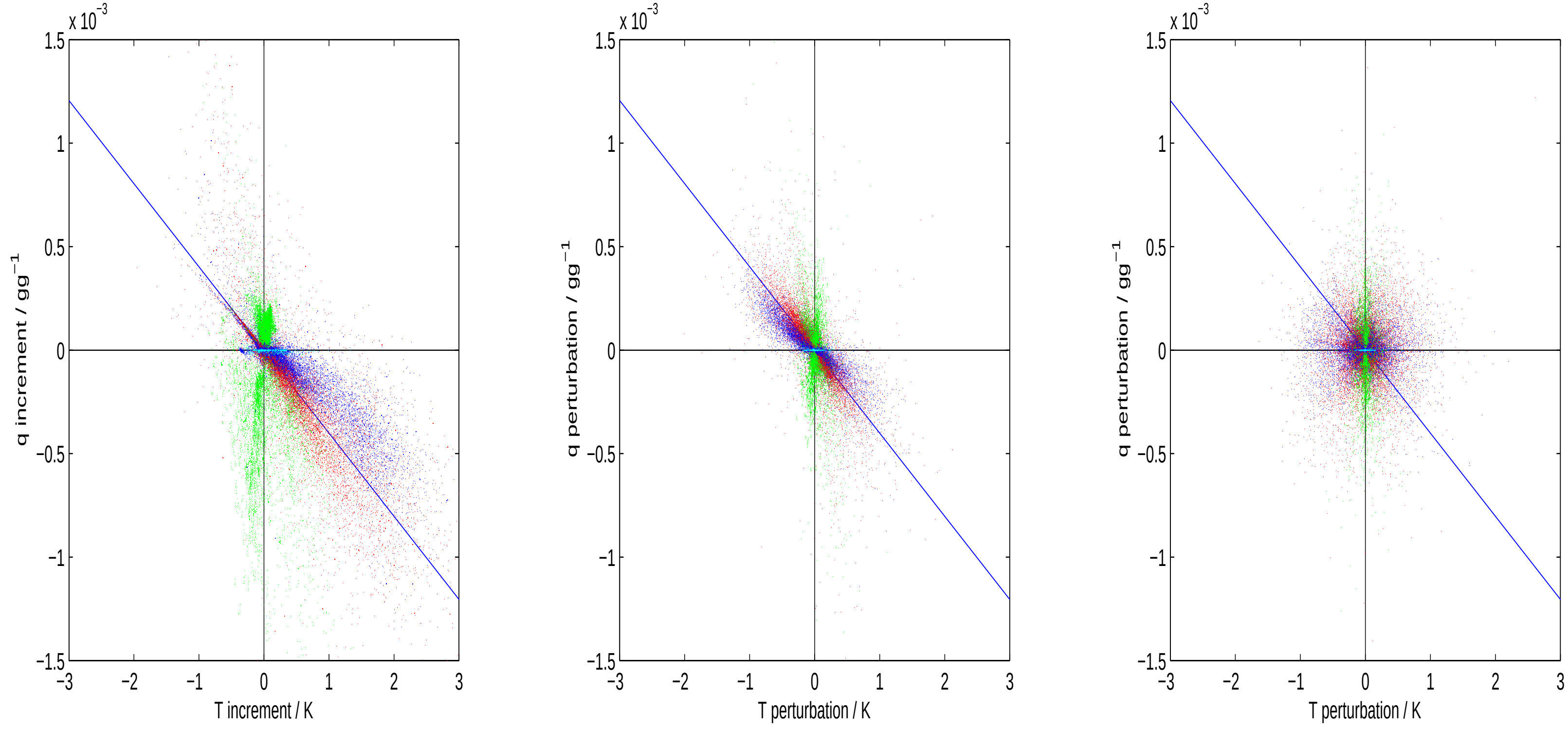
Integrated ensemble spread in T. Black: IC, Blue: mult. noise, Read: mult. noise decorrelated



- Rapid growth in active phase with strong convection and large-scale cloud
- Amplitude beyond 18th stronger than from using fixed random numbers

Test 3

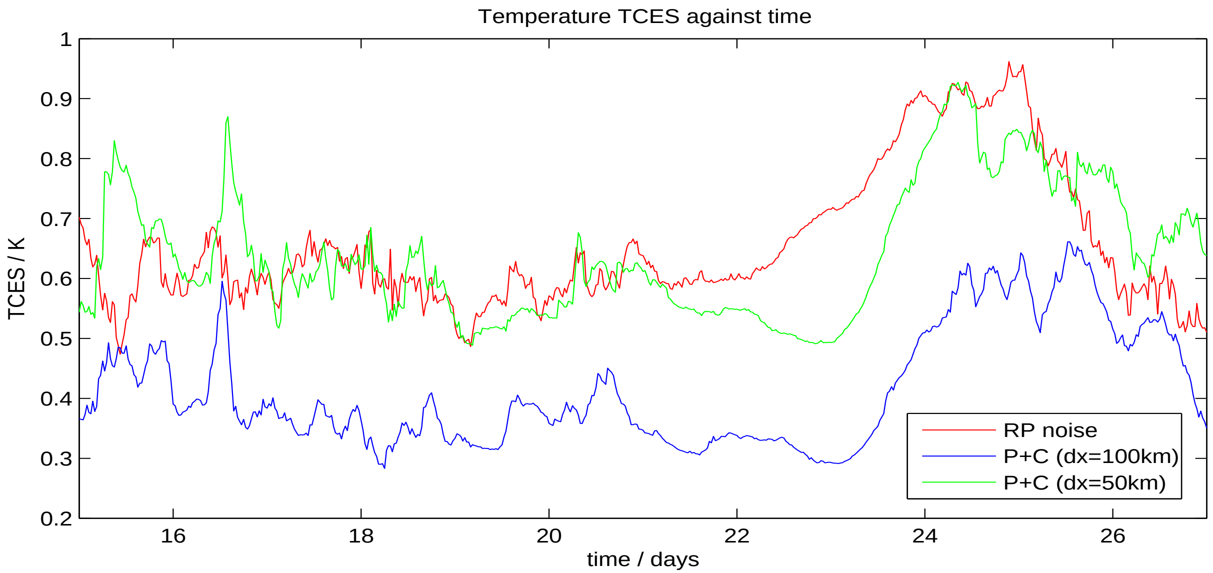
- Tq-increments: default, mult. noise, decorrelated mult. noise



Green: boundary-layer, Red: lower troposphere, Blue: upper troposphere

Test 4

- Spread in Plant-Craig as function of grid-box size



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

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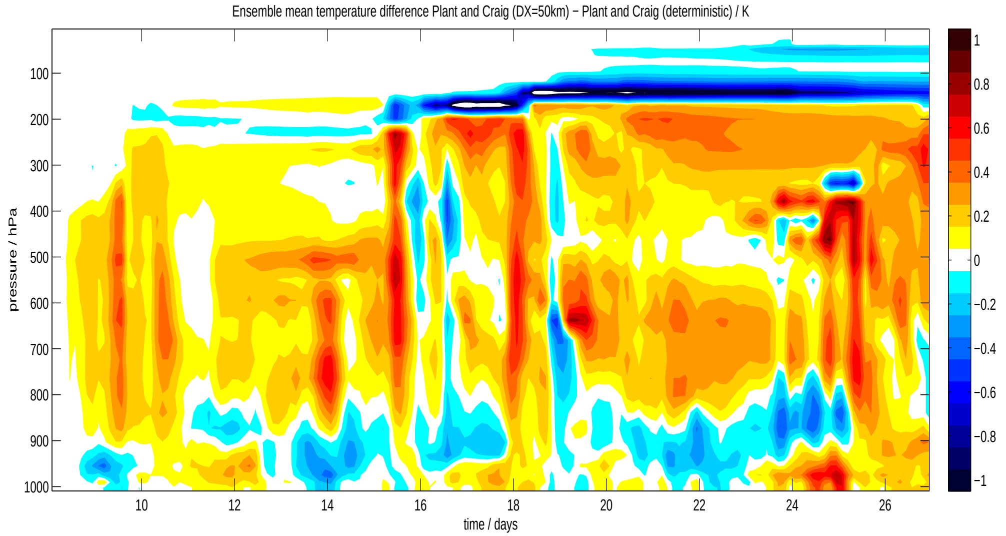
Test 5

- Effect of noise on mean-state with Plant-Craig



- Ensemble mean T difference: Plant-Craig at $\Delta x = 50$km $-$ Plant-Craig deterministic
- Larger than mult. noise or random parameters
- Almost like a different convective parameterisation

Conclusions

- Parameterization methods depend on intrinsic scales and on Δx
- For some purposes, a simple noise source is good enough
- When it isn't, we should search for the physical constraints that are necessary
- This is actually practicable
- $L\Delta q = C_p \Delta T$ when a cloud condenses/evaporates seems useful to know
- Generic and sophisticated methods can produce similar spread but the latter perhaps more likely to shift mean state