Deep convective parameterization: Some issues (and some solutions?)

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23rd February 2009, Cambridge

With thanks to: Michael Ball, George Craig, Laura Davies, Steve Derbyshire

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Let's be honest...

- The perception is that deep convective parameterizations are
  - basically an exercise in engineering / tuning
  - fairly bad

Aim is to argue...

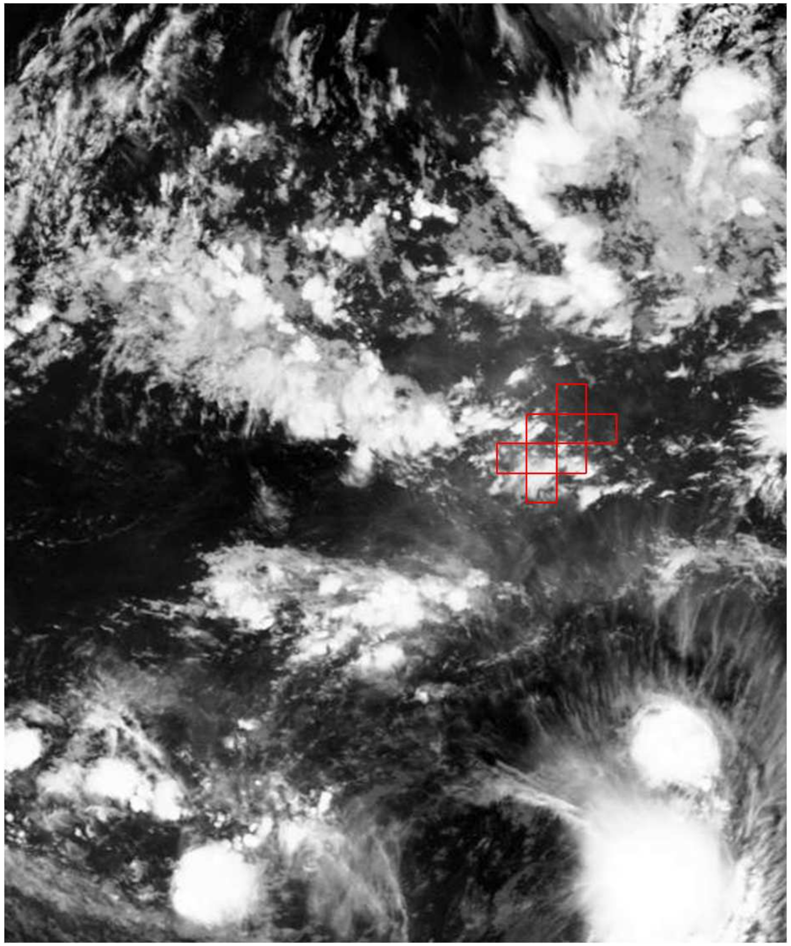
- The perception is that deep convective parameterizations are
  - basically an exercise in engineering / tuning
  - fairly bad
- The reality is that deep convective parameterizations are
  - basically an exercise in science
  - not bad at doing what they've been designed to do!

Outline

- Why do we need a parameterization?
- What are the problems in GCMs?
- A typical parameterization
- Bulk vs. spectral
- Spatial scale separation
- Timescale separation
- Summary

Why do we need a parameterization?

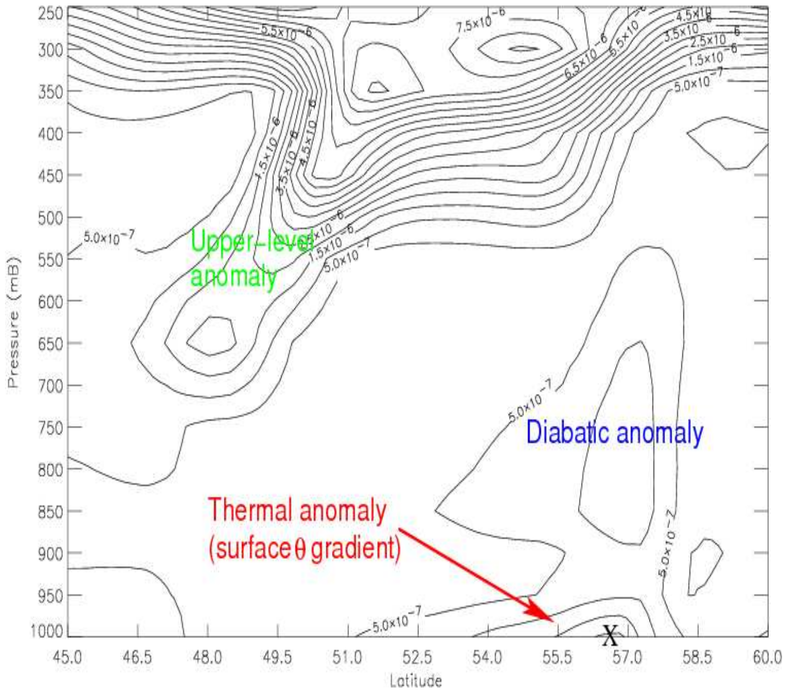
Why a parameterization?

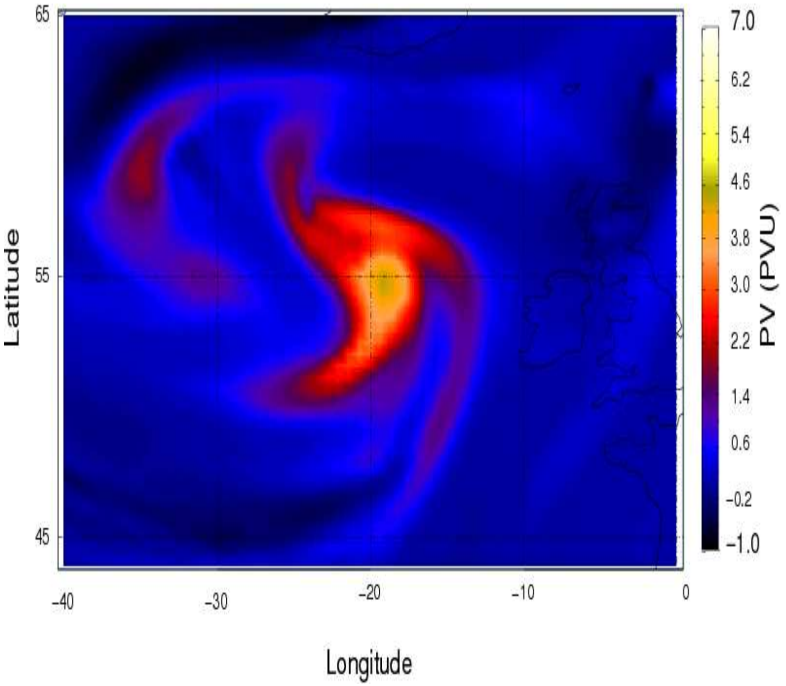


- To stop the model crashing
- Sub-grid scale phenomena important for resolved-scale behaviour
- Deep convection essential in the tropics

Also essential in mid-latitudes

Sections of PV from FASTEX IOP18, at 12Z on 23/02:

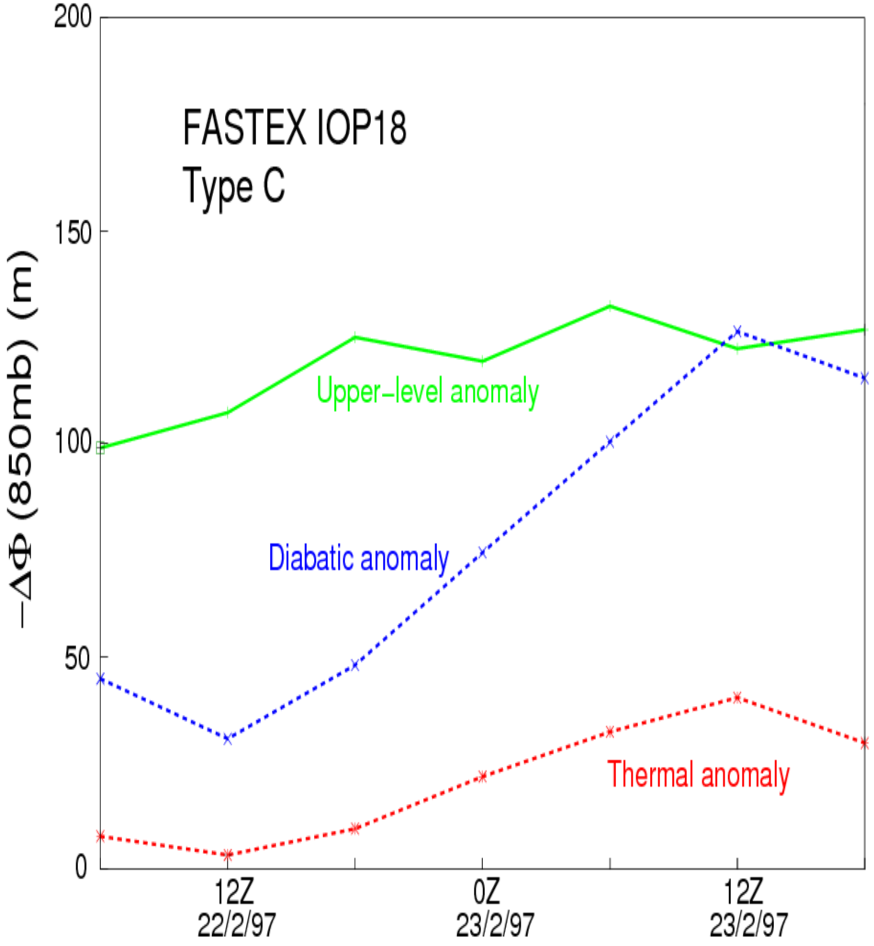




EW section PV from convection, 900mb

(Ahmadi-Givi et al 2003)

Contributions to IOP18



- Diabatic PV anomaly drives deepening
- System does not develop without latent heating

What are the problems as seen in GCMs?

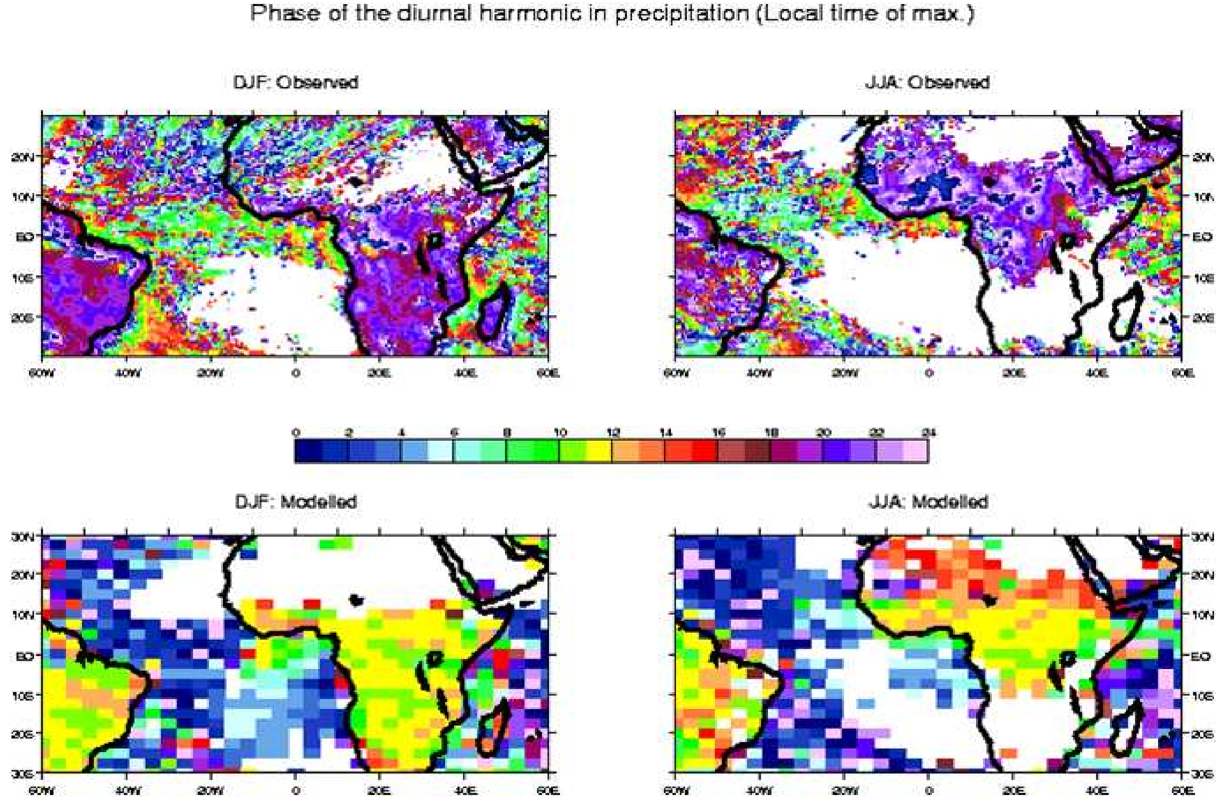
Tropical rainfall in general

- Too many days with weak rainfall
- Extreme rainfall often not captured (very sensitive to parameterization)
- Difficult to get spatial distribution correct
- Difficulties with large-scale, low-frequency organized structures (eg, MJO)

(IPCC 2007)

Diurnal cycle

Observations (top) and model (bottom)



(Yang and Slingo 2001)

Artificial grid-scale noise

- 2hr long animation of a frontal rainband
- 15min timestep

`http://www.met.reading.ac.uk/~sws00rsp/anim/timestep.html`

(Thanks to Stuart Webster)

A typical parameterization

The cumulus ensemble

The Arakawa and Schubert (1974) picture

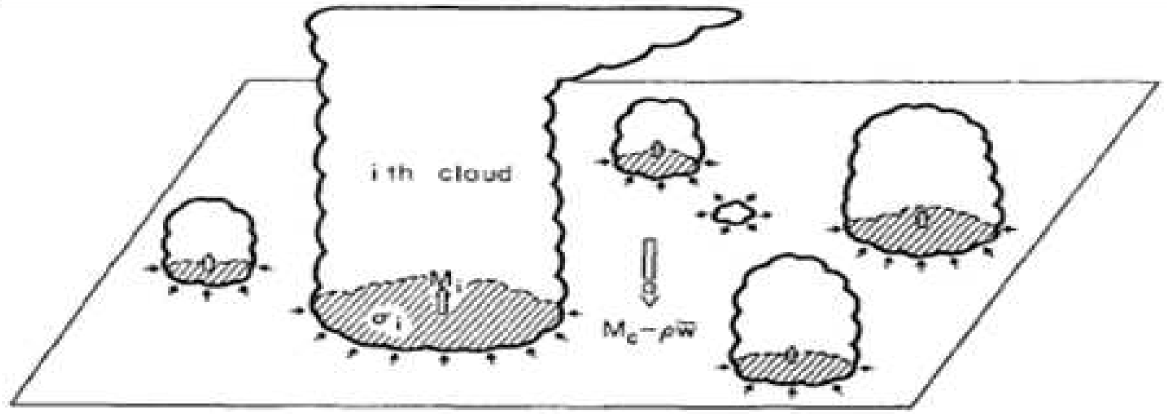
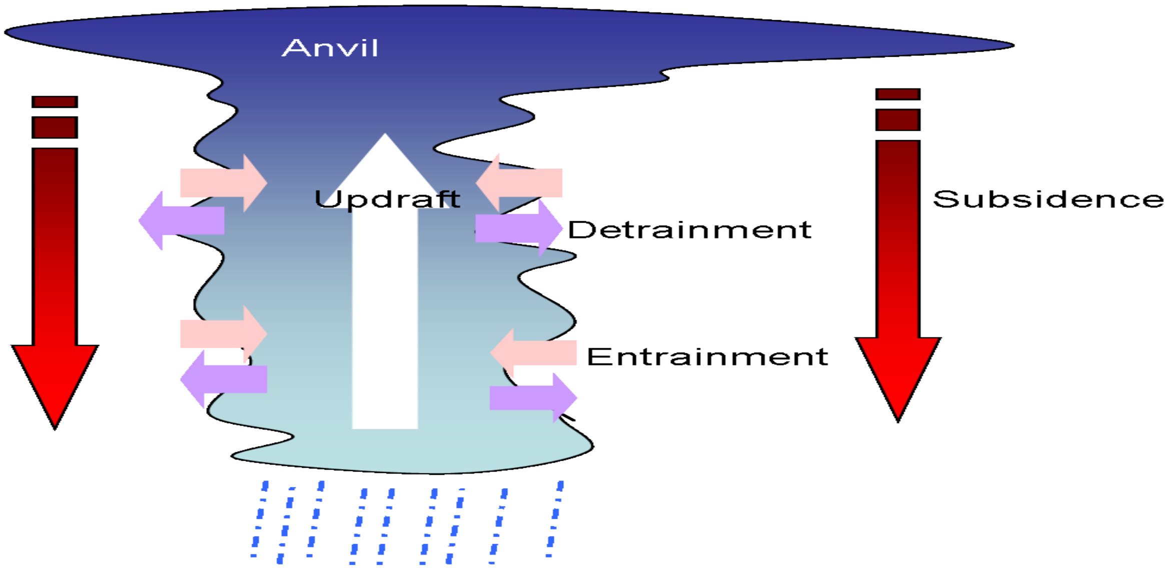


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

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

Entraining/detraining "plume"



Key variable is the mass flux,

$$M_i = \rho A_i \overline{w}_i$$

$$\rho\overline{q'w'} = (1/A_{\mathrm{tot}})\sum_i M_i(q_i - q_{\mathrm{env}})$$

Equations for a plume

$$\frac{\partial \rho \sigma_i}{\partial t} = E_i - D_i - \frac{\partial M_i}{\partial z}$$

$$\frac{\partial \rho \sigma_i q_i}{\partial t} = E_i q_{\mathrm{env}} - D_i q_i - \frac{\partial M_i q_i}{\partial z} - \rho c_i$$

plus similar equations for temperature, liquid water, tracer...

- Average over cloud lifetime to get rid of $\partial/\partial t$
- Integrate from cloud base up to terminating level where the in-cloud buoyancy is zero

To complete the scheme...

In brackets is the simplest, or most common, decision!

- Formulate the microphysics (usually very simple)
- Specify entrainment (spectrum of values, with entrainment rate $\sim 1/r$)
- Determine the detrainment (entraining plume: $D_i = 0$ except at terminating level)
- Determine the mass flux at cloud base for each i, the closure

Closure

- The convection is being forced by some large-scale processes that act to destabilize the atmosphere
- If convection occurs, it will tend to restore stability
- At equilibrium, the large-scale and convective tendencies are in balance
- Good approximation if $\tau_{\mathrm{LS}} \gg \tau_{\mathrm{adj}}$
- CAPE often used as a measure of the instability
- Equilibrium gives $M = \sum M_i$ but its spectral distribution needs further assumptions (e.g., population dynamics, ideal-gas analogy)

Bulk parameterizations

Bulk parameterizations

- A more common approach in practice (MetUM, ECMWF, WRF...)
- Start from same plume equations, and sum over plumes
- Get back essentially the same equations with in-plume values replaced by bulk values,

$$q_B = \frac{\sum_i M_i q_i}{\sum_i M_i}$$

$$E q_{\mathrm{env}} - D q_{\mathrm{env}}^{\mathrm{sat}} - \frac{\partial M q_B}{\partial z} - \rho c = 0$$

Just one “bulk plume” now, so all is much simpler...

The trade-off for a bulk scheme

- Setting the total entrainment E is harder than setting E_i
- Detrainment D becomes relevant at all heights

Is it better to "guess" E and D or to "guess" the spectral distribution of mass flux?

The price of a bulk scheme

- Some subtle effects on termination level and equilibrium closure

  (previous arguments don't quite follow through: Plant 2009a)

- All the simplifications hinge on an extra "gross assumption" about the detrained cloud liquid water,

$$l_{Di} = l_B = \frac{\sum_i M_i l_i}{\sum_i M_i}$$

- For variables other than T, q and l there is no simplification!

For example...

- Chemical and tracer transports (say) are not correct as normally computed in a bulk framework

$$E\phi_{\mathrm{env}} - D\phi_B - \frac{\partial M_c \phi_B}{\partial z} - S_B = 0$$

should read

$$E\phi_{\mathrm{env}} - D\phi_B \left[\frac{M_c \sum_i D_i \phi_i}{D \sum_i M_i \phi_i} \right] - \frac{\partial M_c \phi_B}{\partial z} - S_B = 0$$

- Decompose bulk plume into individual plumes! (Lawrence and Rasch 2005)

Large-numbers assumption and space-scale separation

Is the GCM grid “large-scale”?

- A determinstic parameterization gives a unique response for a given state of the parent model
- This assumes that a large-scale state exists: a region containing many individual clouds but with tolerably uniform forcing
- It also assumes the model grid box to be a large-scale region

Why stochastic?

- If a large-scale state really exists, but the number of cumulus clouds in a grid box is not large then...
  - ... convection on the grid-scale is unpredictable
  - ... but drawn from a distribution dictated by the large-scale
  - ... so a stochastic parameterization is needed!
- Fluctuating component of sub-grid motions may have important interactions with large-scale (noise-induced drift etc.)

Plant and Craig parameterization

Mass-flux formalism...

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

The stochastic component

- Deterministic limit if N in the grid box is large
- It then tends to a spectrum of plumes with varying entrainment rates in the Arakawa and Schubert (1974) tradition
- Away from the limit, stochastic with the noise having a physical basis
- Physical noise $>>$ numerical noise from scheme

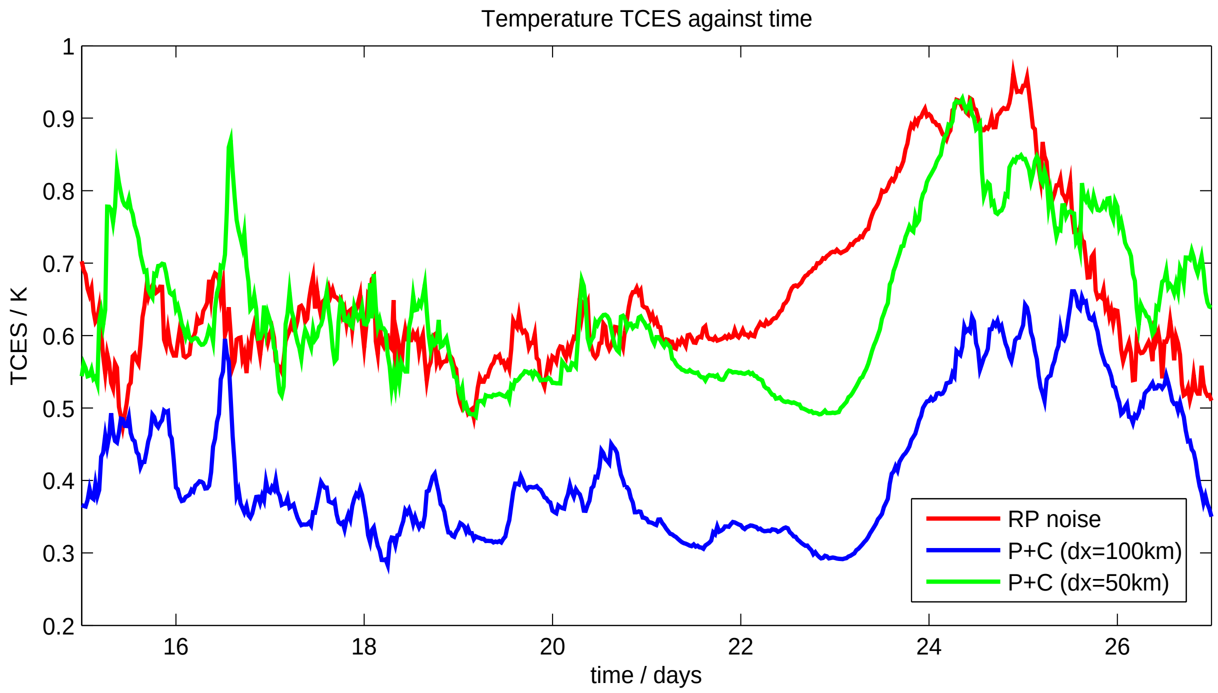
Example of use

Single-column tests of GCSS case 5 (Ball and Plant 2008),

- Mean-state comparable to other convective parameterizations
- For grid-box area of 50km, the variability is similar to that from
  - a poor-man's ensemble of deterministic parameterizations
  - generic methods designed to represent model uncertainty

    (multiplicative noise, random parameters)

GCSS Case 5 Test



- Future/current tests in aqua-planet GCM and in Met Office short-range ensemble (MOGREPS)

Implications

1. GCM grid-box may not be a large-scale state
2. Convective instability is released in discrete events
3. Discrete character is a major source of variability for $\Delta x \lesssim 50$km

NB: we are considering statistical fluctuations about equilibrium, not systematic deviations away from equilibrium

Equilibrium assumption and timescale separation

Equilibrium assumption

If $\tau_{LS} \gg \tau_{adj}$, past history of forcing is effectively encoded in the current state of the atmosphere

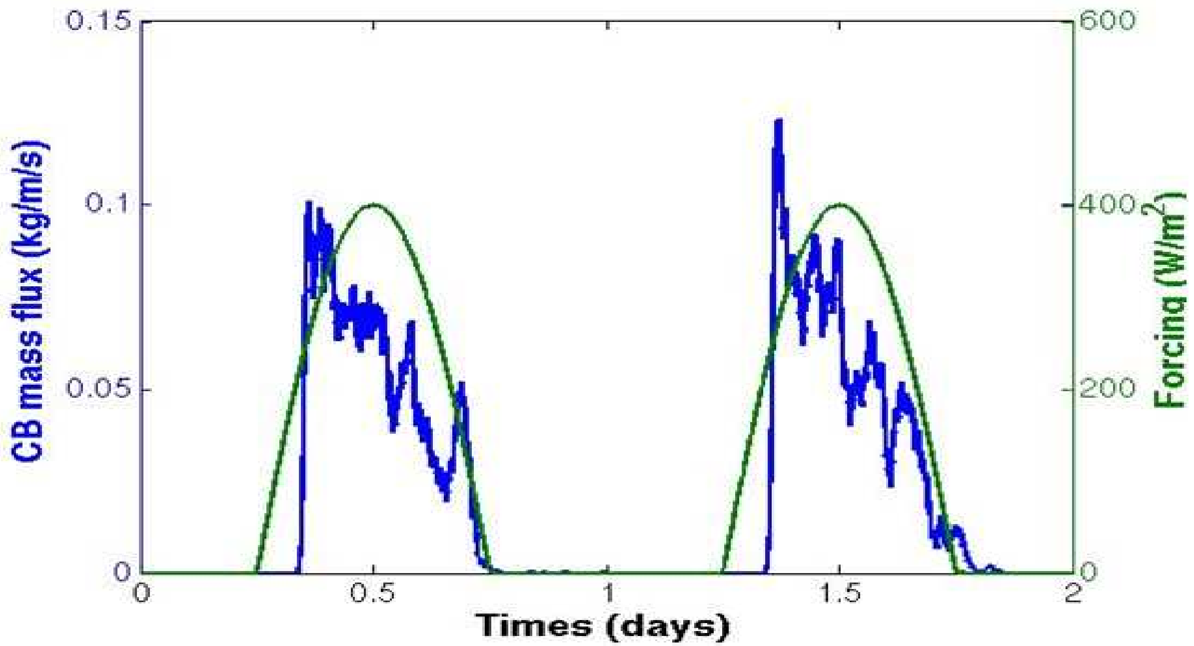
- What forcing timescale is “large enough”?
- What behaviour might occur if $\tau_{LS} \not\gg \tau_{adj}$?
- What is the physical mechanism?

- Hard to control τ_{adj}, but we can vary τ_{LS}...

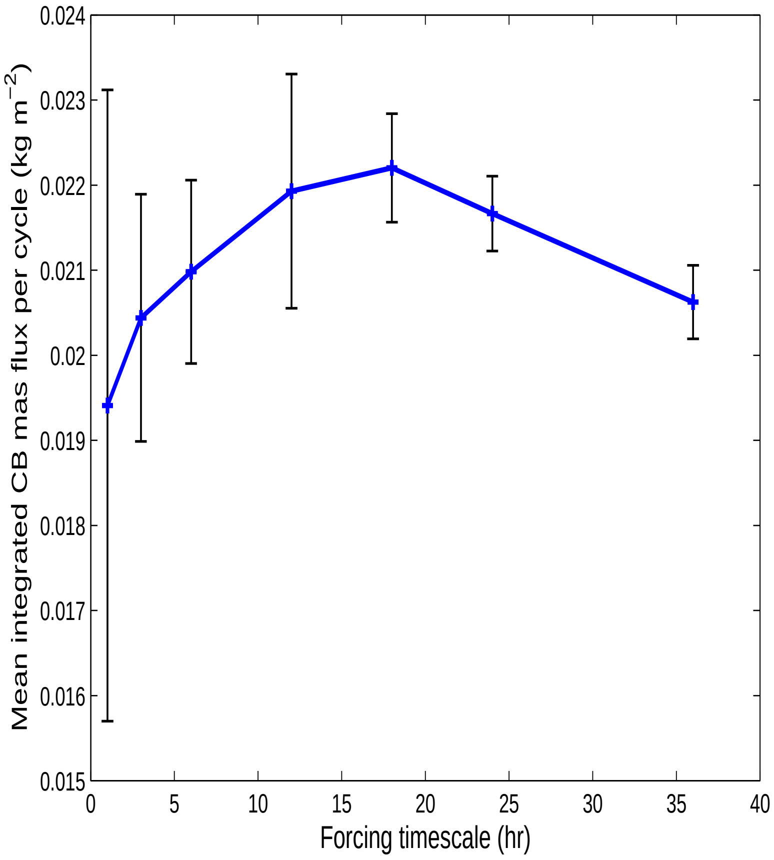
Davies 2008; Davies et al. 2009

The CRM Experiments

- Using Met Office LEM, 1km horizontal resolution on $64x64\text{km}^2$ domain
- Forced by prescribed surface fluxes



Variations in Convection Per Cycle



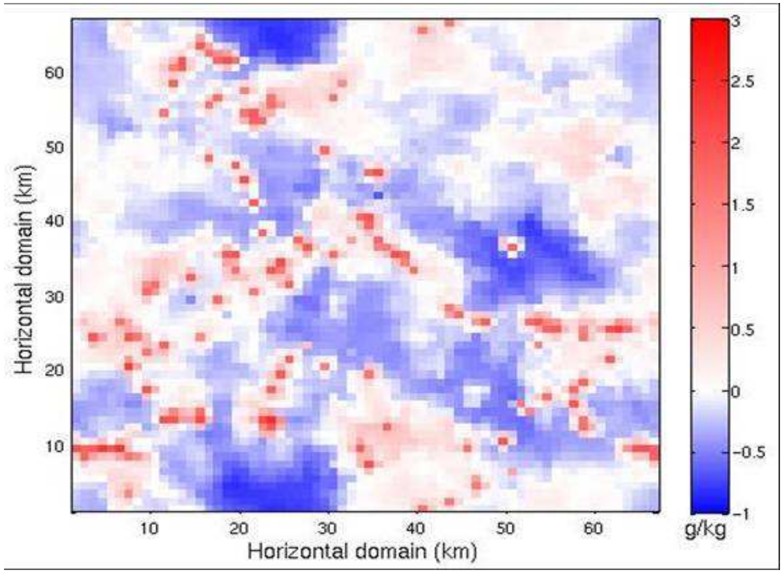
- Necessary condition for equilibrium is that time-integrated convection should be the same cycle-to-cycle
- Enhanced variability at $\tau_{LS} \lesssim 12$hr
- Negative correlations between successive cycles at these timescales

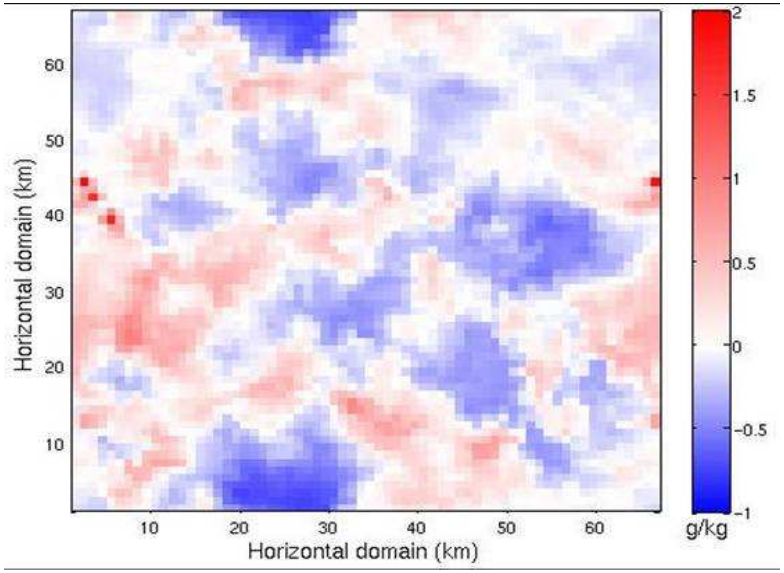
Memory mechanism

- Cycle-to-cycle variability not explained by differences in domain-mean profiles
- i.e., memory is not carried by large-scale state
- Convection develops coherent moisture structures on scales of ~ 10–20km
- For the shorter τ, power at these scales is retained during the break in convective activity

Spatial Water Vapour Anomaly

Snapshots during active convection (left) and just before onset of convection (right), for $\tau_{LS} = 3$h





Implications

- Memory effects found for timescales $\lesssim$ 12hr
- For $u \sim$ 10ms^{-1}, this translates to a spatial scale of $\sim$ 400km
- To handle rapid and/or localized forcing mechanisms, the perfect parameterization would be non-local and prognostic

Summary

Other important issues

- Cumulus assumed non-interacting
  - But they self-organize, tending to cluster together (Cohen 2001, Davies 2008)
- Is there really a scale separation at all?
  - Some evidence against. (Yano et al 2004, Neelin et al 2008, Jordan 2008)
- How to include lifecycle aspects? (Plant 2008)
- How should we handle chemical transports?
  - Should I be worried about this?

Conclusions

- The archetypal convective paramerization is based on simple bulk model of entraining/detraining plume
- It assumes clean scale separations in space and time
- If grid boxes are not large, fluctuations become important
    - can account for these with stochastic component
- If forcing is fast and/or local, memory becomes important

A Personal View

- Perception is that deep convective parameterizations are
  - basically an exercise in engineering / tuning
  - fairly bad
- Reality is that deep convective parameterizations are
  - basically an exercise in science
  - not bad at doing what they've been designed to do!
  - sometimes bad at things outside their design spec.

A Personal View

- It is possible to make major improvements to convective parameterizations
- The way to improve them is to try to do better science
- First steps are underway: some of the fundamental assumptions are under attack...