Limitations of Equilibrium
Or:
What if $\tau_{LS} \not\gg \tau_{adj}$?

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Outline

Deliberately depart from a key quasi-equilibrium assumption

- The timescale separation issue
- A simple model with memory
- CRM results with variable forcing timescale
- Memory and its origins
- Conclusions / implications

Timescale Separation

Adjustment Timescale

- Consider an “adjustment timescale” τ_{adj}
- Describes rate at which a pre-existing convective instability would be removed by convective activity in the absence of forcing
- Key assumption of quasi-equilibrium thinking is that $\tau_{LS} \gg \tau_{adj}$
- Parameterizations often include some such adjustment timescale in computing the closure
- Their behaviour is sensitive to the timescale used

Adjustment Timescale

- May be related to cumulus lifetime?
- Or related to time taken for gravity waves to travel between clouds?

  i.e., to communicate local temperature perurbations from clouds throughout environment
- For a step change in forcing, adjustment of mass flux is proportional to cloud spacing in unadjusted state (Cohen and Craig 2004)
- Implies that it depends on magnitude of forcing

Timescale Separation

- Arakawa and Schubert (1974), p691

  Usually the large-scale forcing is changing in time and therefore the cumulus ensemble will not reach an exact equilibrium. The properties of the cumulus ensemble ... depend on the past history of the large-scale forcing, but this dependency should be significant only within the time scale of the adjustment time.

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

Timescale Separation

- Arakawa and Schubert, continued...

  We assume that this is the case for the cumulus ensembles we wish to parameterize. We call this assumption "the quasi-equilibrium assumption". It is also an assumption on parameterizability, if by parameterization we mean a relation between the properties of the cumulus ensemble and the large-scale variables at some instant.

Separation Issues

But...

- What forcing timescale can be considered “large enough”?
- What happens as quasi-equilbrium starts to break down?

Simple Model for Convective Memory

Simple Model

Two-layer model of atmosphere and surface

$$\frac{dT}{dt} = \mathrm{COOL} + Q_1 \tag{1}$$

where Q_1 adjusts to a rate R with a memory timescale t_{mem},

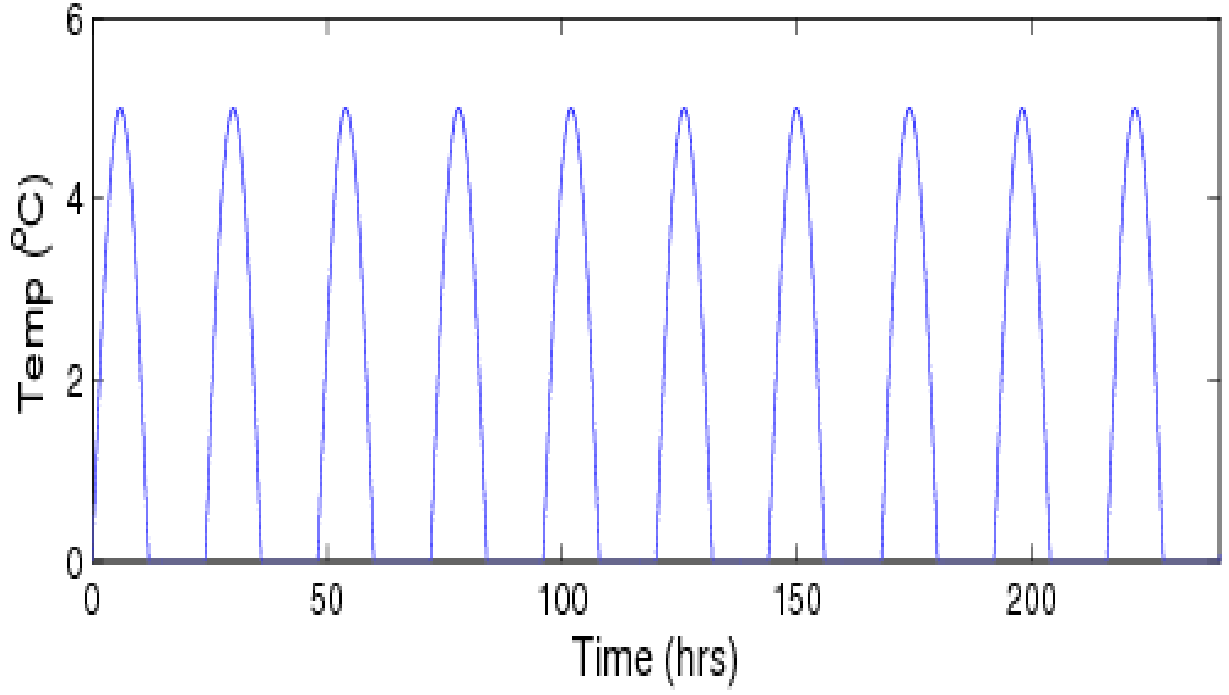
$$\frac{dQ_1}{dt} = \frac{R - Q_1}{t_{\mathrm{mem}}} \tag{2}$$

and the rate R is such as to produce a neutral temperature with a "closure" or adjustment timescale t_{close}

$$R = \mathrm{MAX}\left(\frac{T_{\mathrm{surf}} - T}{t_{\mathrm{close}}}, 0\right) \tag{3}$$

Simple Model Forcing

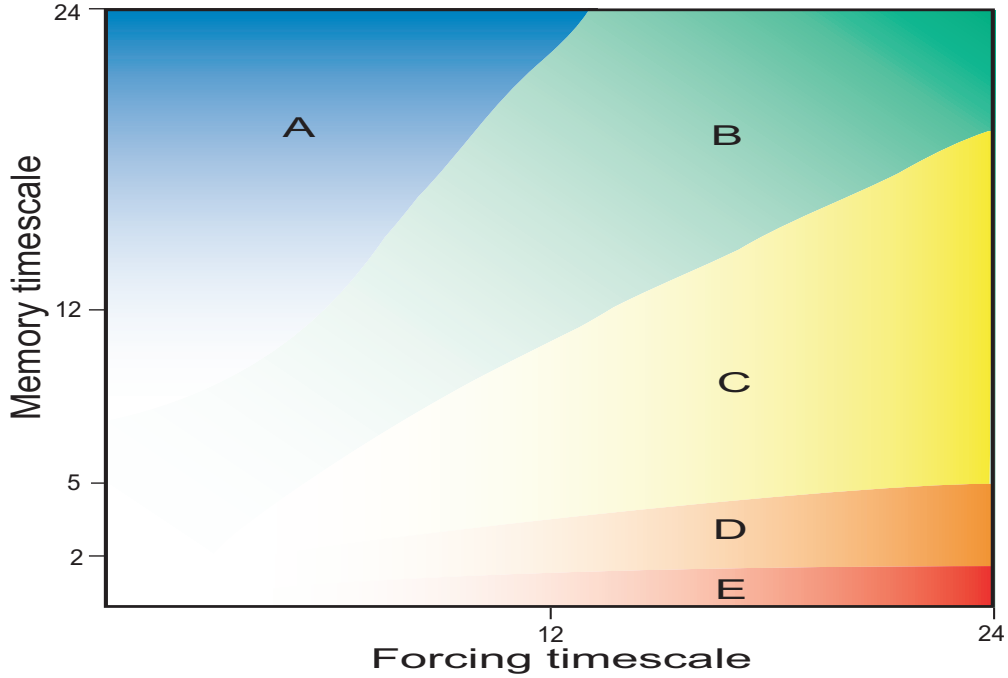
Surface temperature prescribed, and is characterized by a timescale τ



Half of a sine wave during “day”, constant at “night”

Regime Diagram

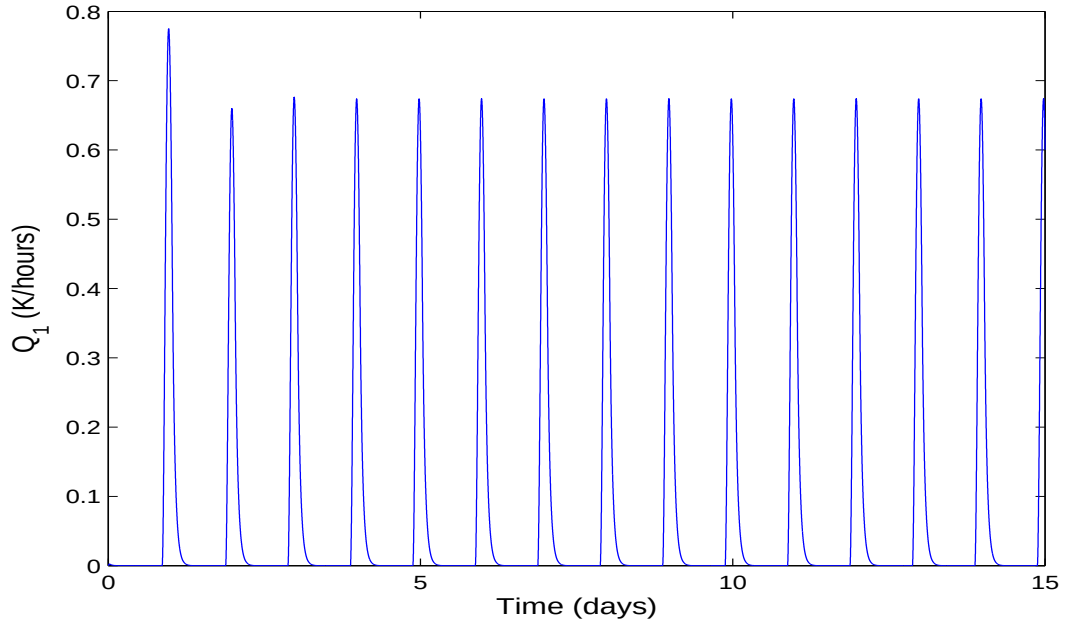
Qualitative diagram for $t_{\text{close}} = 1\text{hr}$



Choose $\tau = 24\text{hr}$ and look at regimes for increasing t_{mem}

Regime Type E

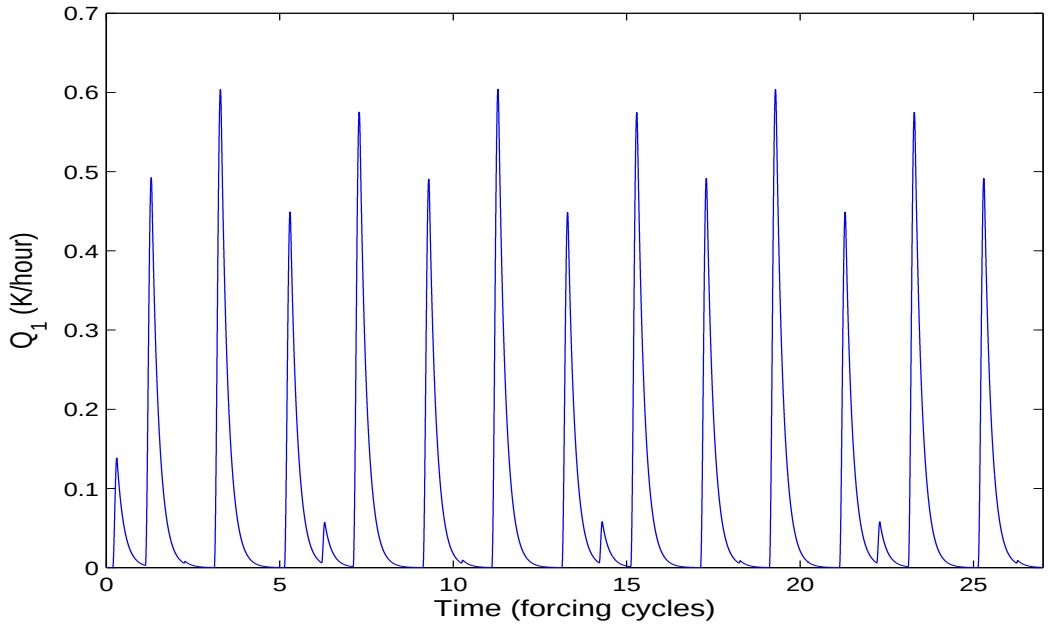
Type E: $t_{\text{mem}} << \tau$, repetitive response, dominated by evolution of forcing



Q_1 timeseries for $t_{\text{mem}} = 1\text{hr}$

Regime Type D

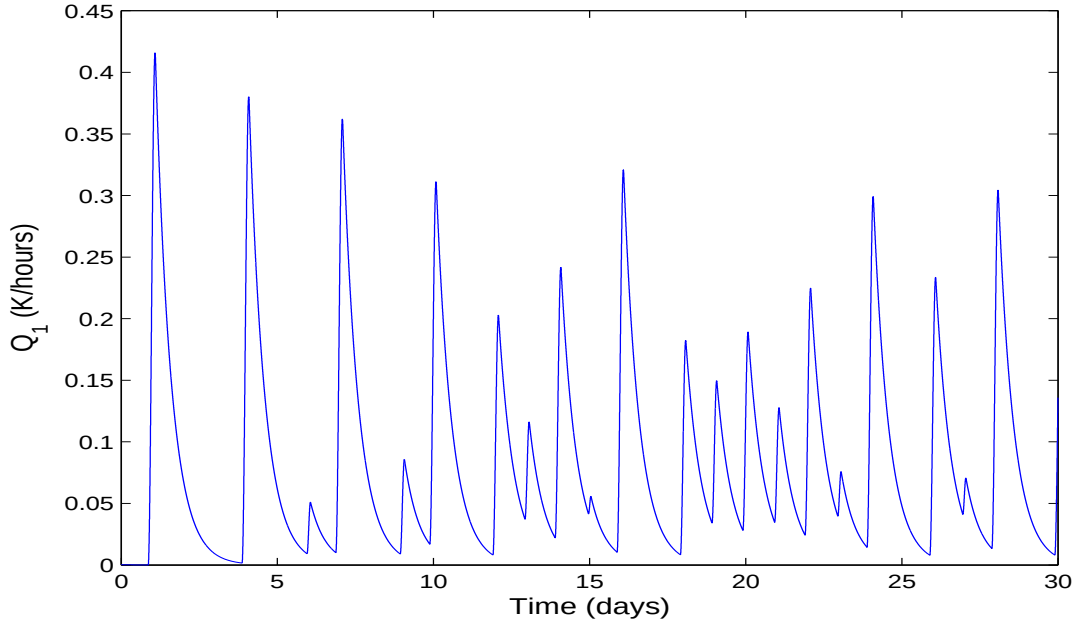
Type D: a transitional regime, with variability and skipped cycles



Q_1 timeseries for $t_{\text{mem}} = 5\text{hr}$

Regime Type C

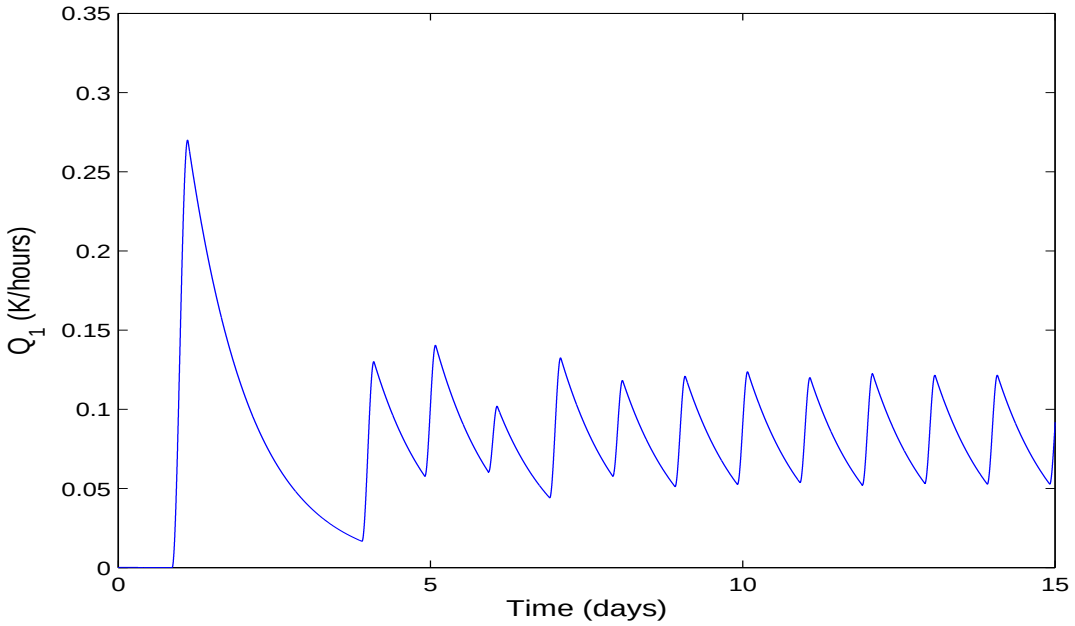
Type C: the heating over each forcing cycle is variable



Q_1 timeseries for $t_{\text{mem}} = 12\text{hr}$

Regime Types B and A

Type B: heating oscillates about a mean response



Q_1 timeseries for $t_{\text{mem}} = 24\text{hr}$

Type A: $t_{\text{mem}} >> \tau$, very slow response, not adjusted after 20+ cycles

In summary

- As t_{mem} increases to $\sim \tau$ the response is not directly related to current forcing
- Implies feedback, with current heating dependant on the time-history of the convection
- Are there such regimes for atmospheric convection?
- Hard to vary t_{mem} (!), but we can vary τ....

CRM Results for Variable τ_{LS}

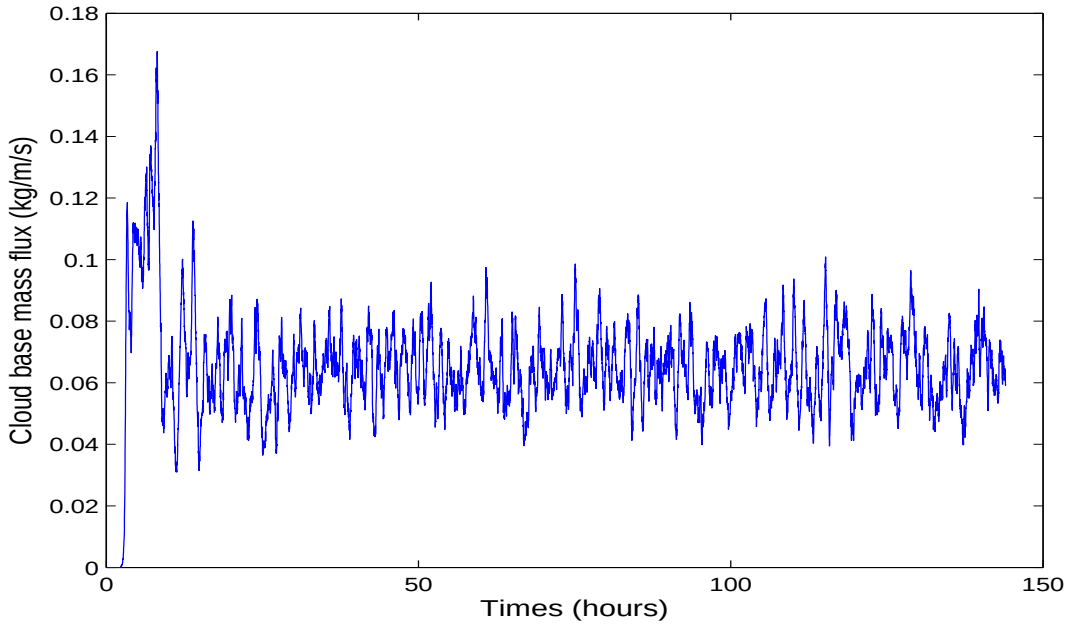
The CRM Experiments

Using Met Office LEM

- 1km horizontal resolution on $64x64\text{km}^2$ domain
- Prescribed radiative cooling of troposphere, constant with height
- No wind shear imposed, $f = 0$
- Run to radiative-convective equilibrium with prescribed sensible and latent heat fluxes
- Then vary surface fluxes: half sine wave during “day” and switched off at “night”
- Not a diurnal cycle simulation: e.g., no shallow convection phase

Equilibrium: "Weak" Definition

If τ is long (e.g., for constant forcing), equilibrium state easily defined...



Equilibrium: "Weak" Definition

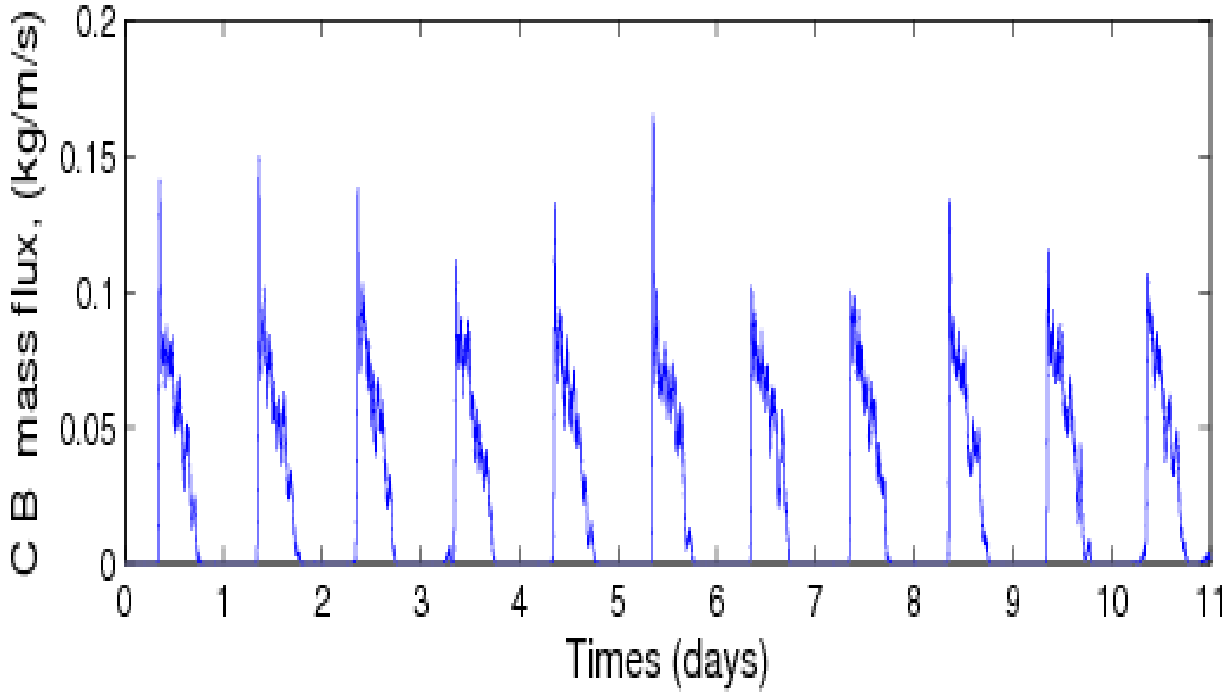
If τ is finite...

- A strict definition is to compare the instantaneous convective heating to the instantaneous forcing
- Not satisfied by convection due to adjustment

  Does not respond instantaneously: eg, when forcing first switches on
- Here we consider a "weak" definition of an equilibrium: compare the total convective heating to the total forcing, integrated over the forcing cycle
- A balance between these is a necessary condition for AS's quasi-equilibrium

Timeseries of Mass Flux

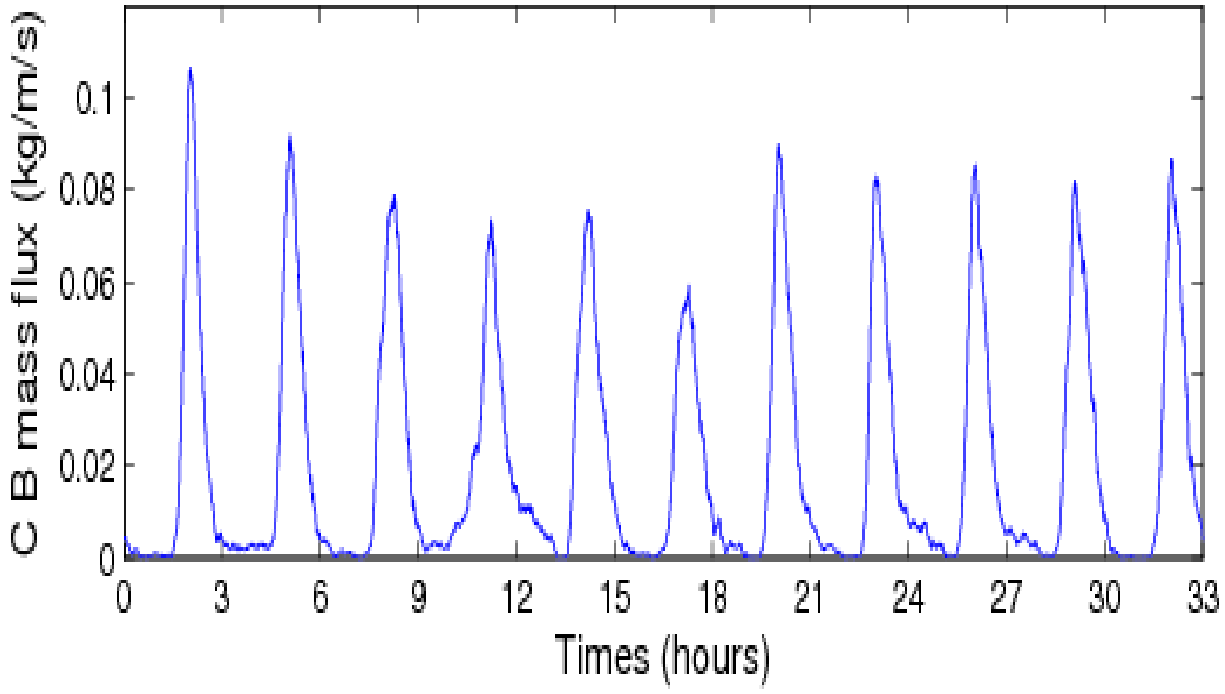
For $\tau = 24$hr, with similarities to regime E



Type E: repetitive response, dominated by evolution of forcing

Timeseries of Mass Flux

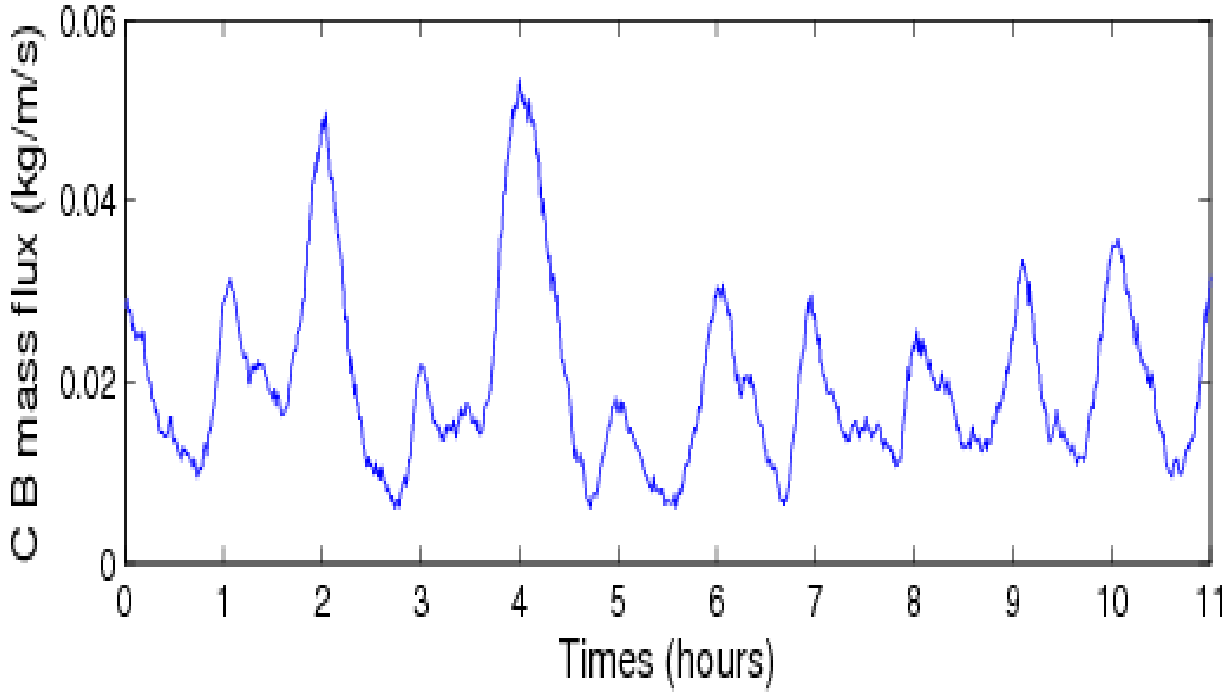
For $\tau = 3$hr, with similarities to regime C



Type C: the heating over each forcing cycle is variable

Timeseries of Mass Flux

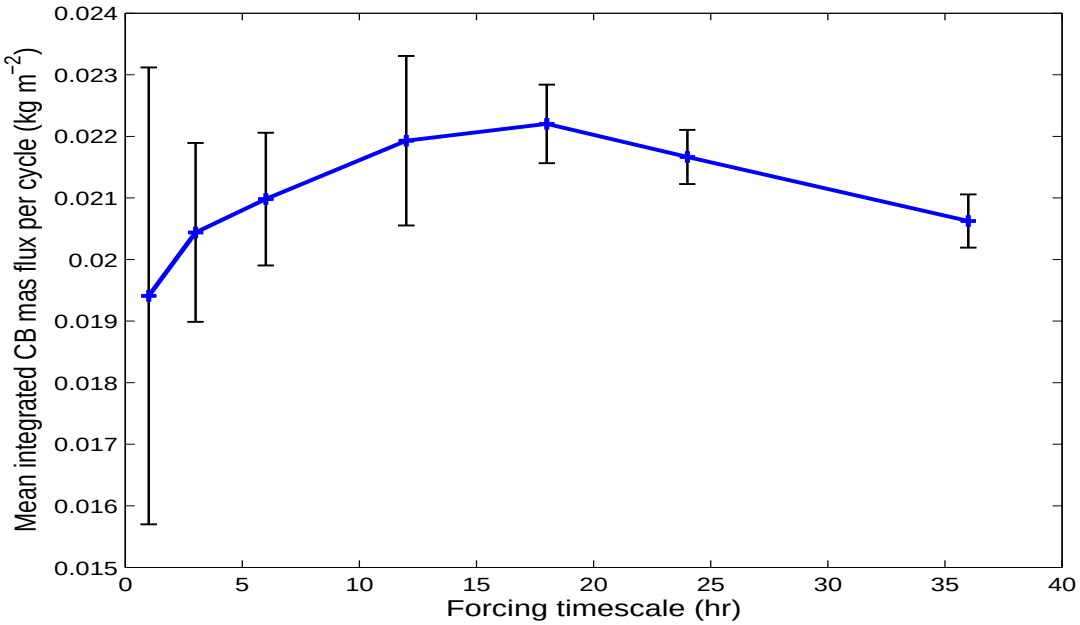
For $\tau = 1$hr, with similarities to regime B



Type B: heating oscillates about a mean response

Variations in Convection Per Cycle

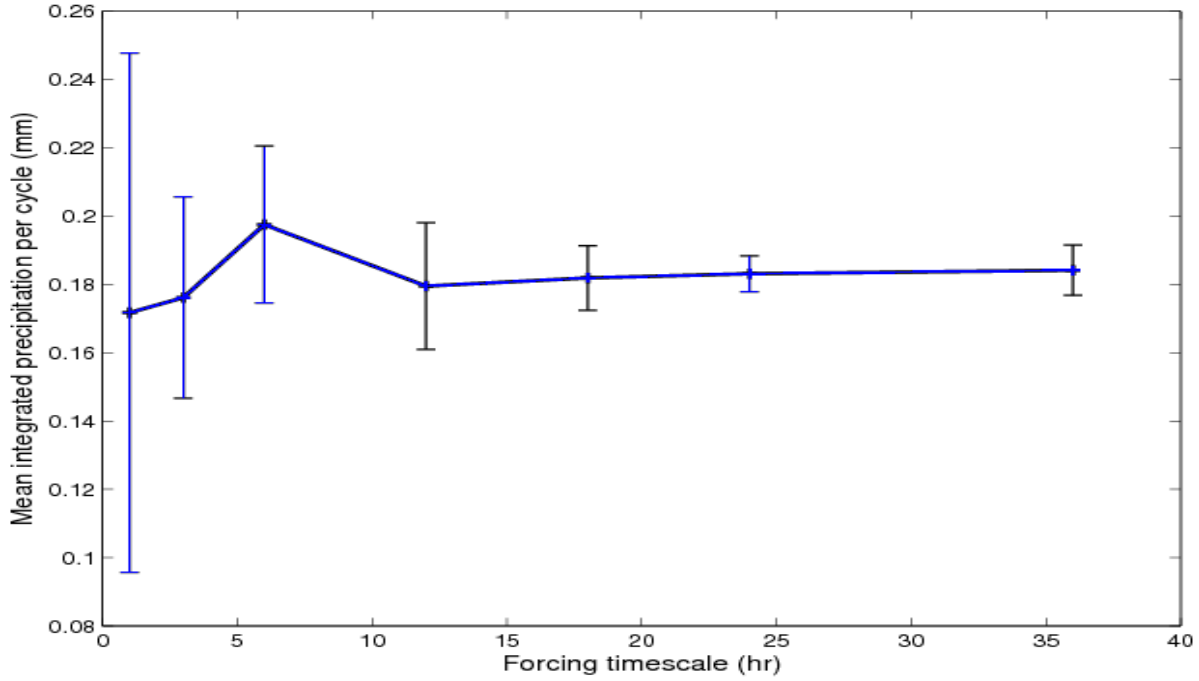
As measured by cycle-integrated cloud base mass flux,



Enhanced variability at $\tau \lesssim 12$hr

Variations in Convection Per Cycle

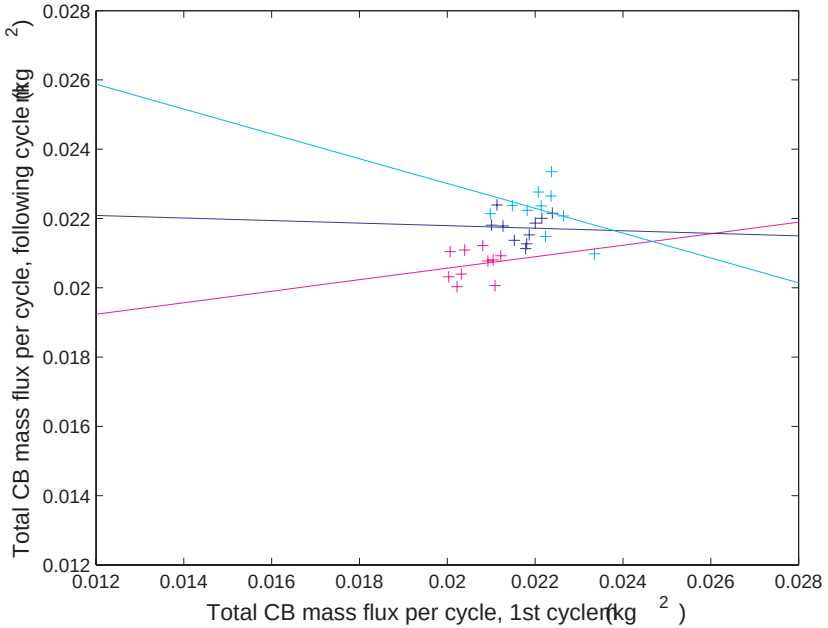
As measured by cycle-integrated precipitation,



Enhanced variability at $\tau \lesssim 12$hr

Feedback from one cycle to the next?

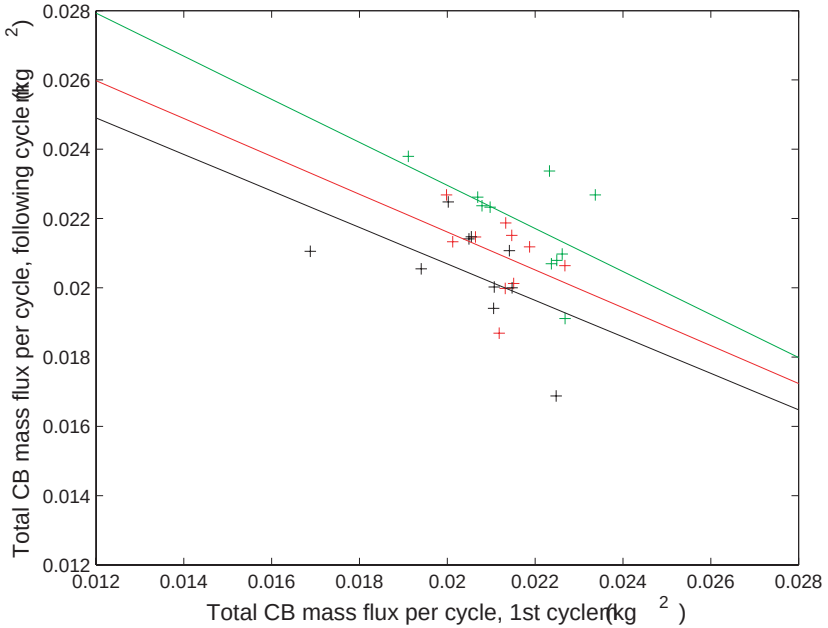
For $\tau =$36h (pink), 24h (dark blue), 18h (light blue)



No correlation between convection on successive cycles for $\tau \gtrsim$ 18hr

Feedback from one cycle to the next?

For $\tau =$12h (green), 6h (red), 3h (black)



$R^2 \sim -0.5$ for $3 \lesssim \tau \lesssim$ 12hr

Physical Origins of Memory

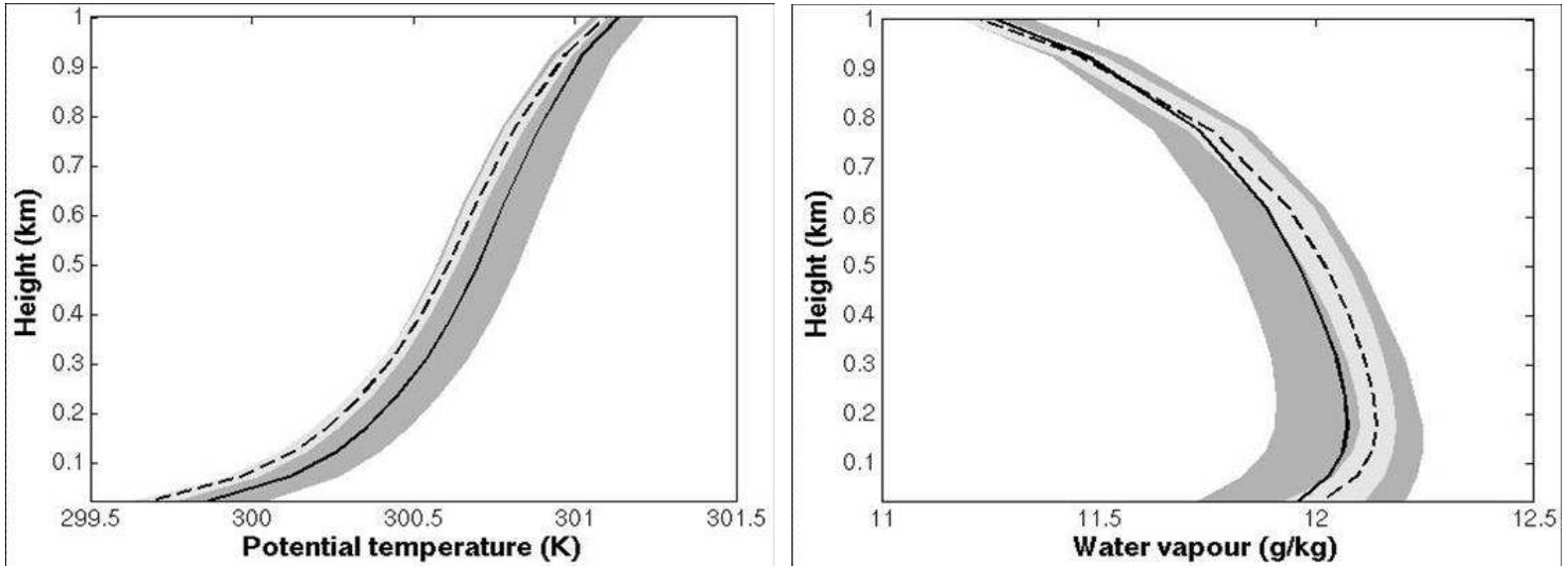
Mean State

Is the cycle-to-cycle variability explained by differences in domain-mean profiles?

- Domain-mean profiles of θ and q_v at start of forcing conditioned on the convection occurring in the following cycle:
  - integrated mass flux exceeds mean (strong cycles)
  - integrated mass flux exceeds mean (weak cycles)

Mean State

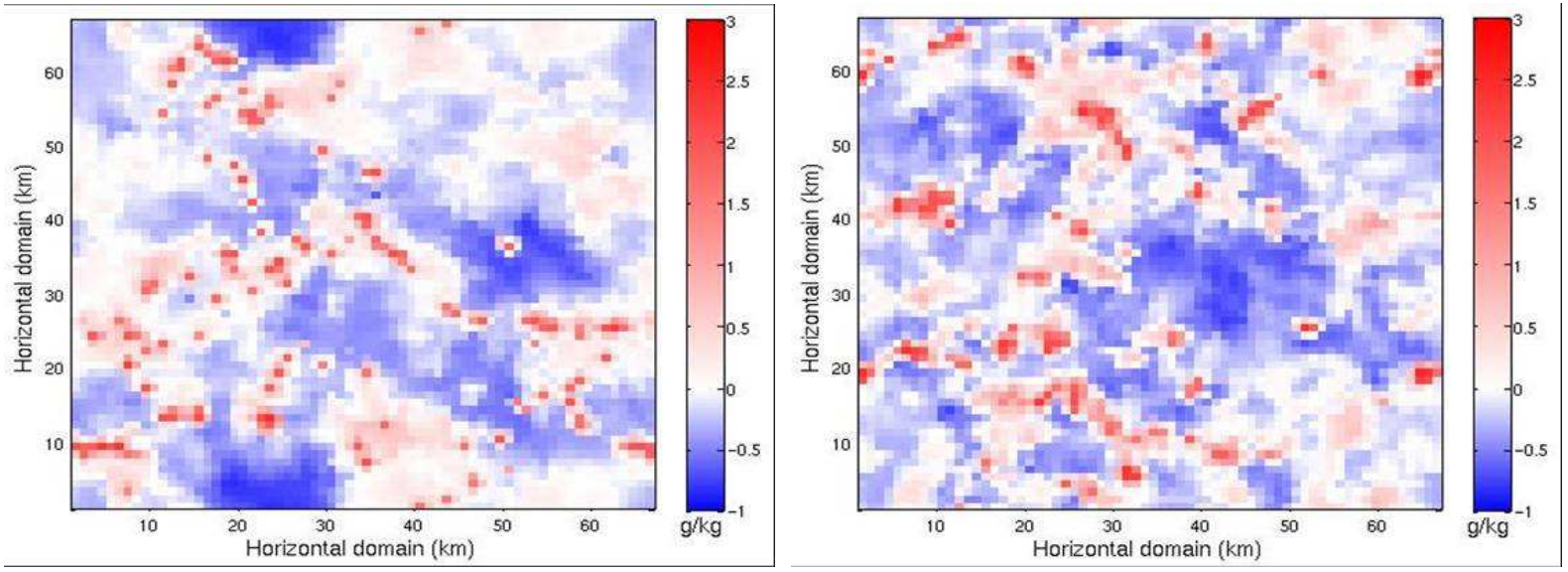
Solid line and dark shading for strong cycles; dashed line and light shading for weak cycles.



Strong/weak difference < variations between strong cycles

Spatial Water Vapour Anomaly

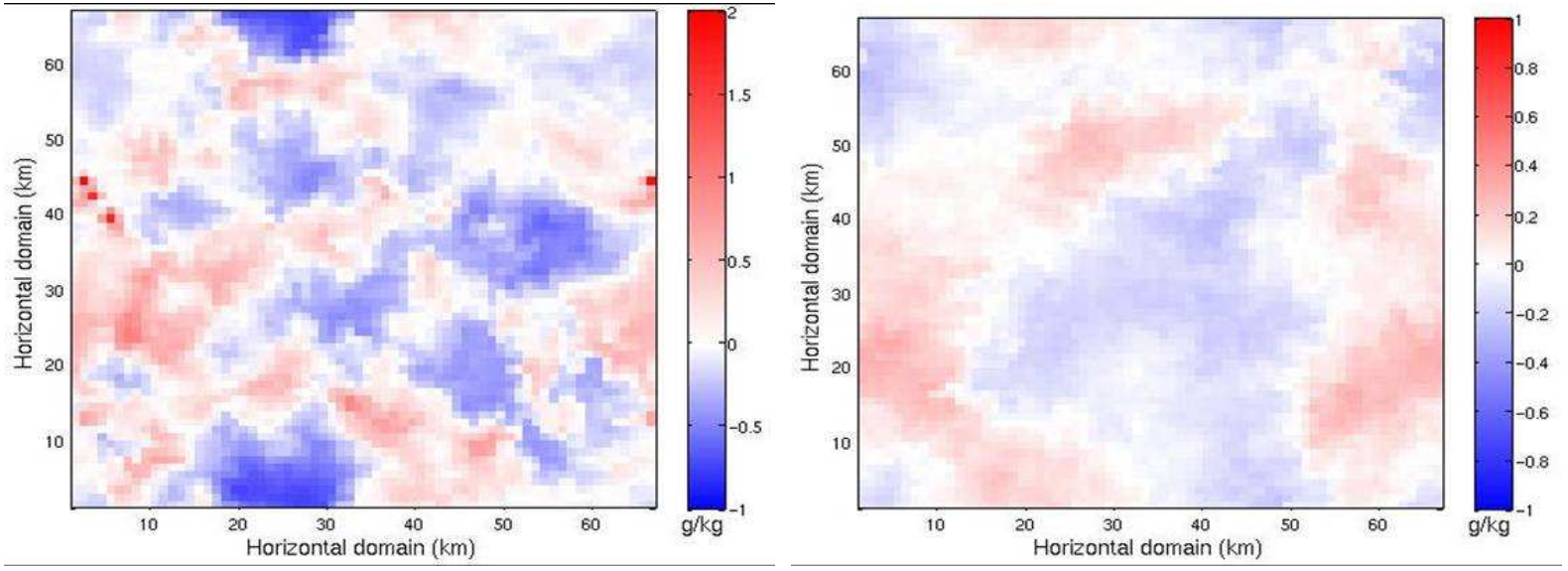
Snapshots during active convection, for $\tau = 3$h (left) and $= 24$h (right)



Convection develops coherent structures on scales of $\sim$ 10–20km

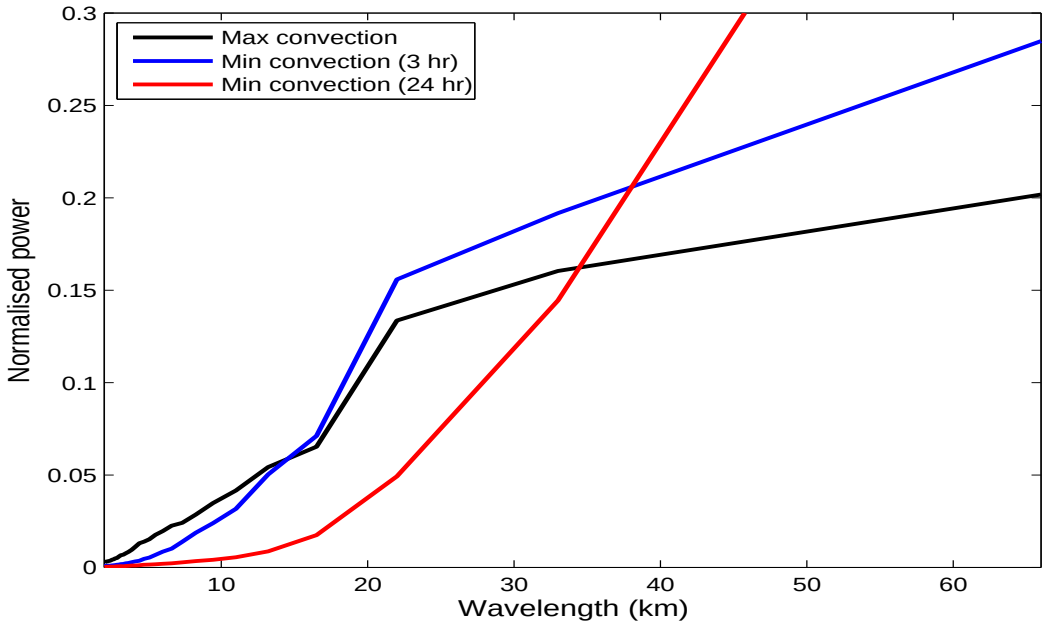
Spatial Water Vapour Anomaly

Snapshots just before onset of convection, for $\tau = 3$h (left) and $= 24$h (right)



Note different scales used.

Power Spectrum of RH



For longer τ, the power at intermediate scales is lost during the break in convective activity

Conclusions

- Memory appears to be carried by spatial structures in the moisture field, not in the domain-mean state
- Memory effects found for timescales $\lesssim 12$hr
- For $u \sim 10\text{ms}^{-1}$, this translates to a spatial scale of 500km
- Suggests that for forcing mechanisms with scales $\lesssim 500$km, convection may not be in quasi-equilibrium
- Convection in upstream grid boxes may be relevant
- The perfect parameterization might have non-local aspects, and not be purely 1D?