Investigating the equilibrium assumption between convection and the forcing

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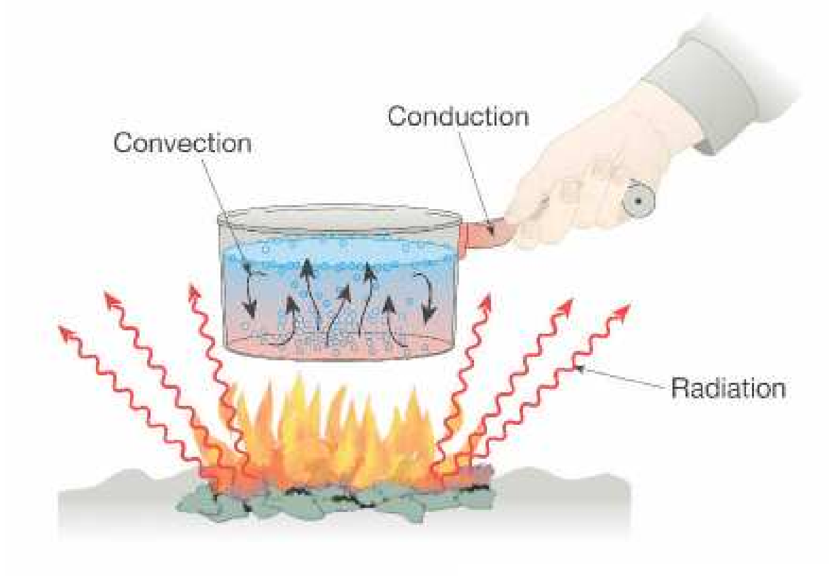
Thanks to:
Marc Stringer, Alan Grant, Steve Woolnough and Jeffrey Chagnon.

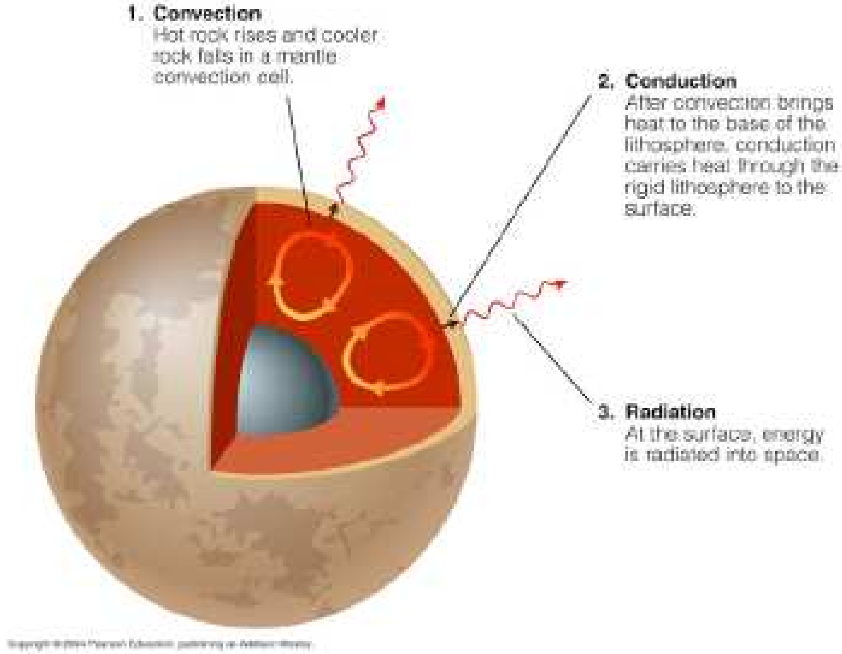
Seminar plan

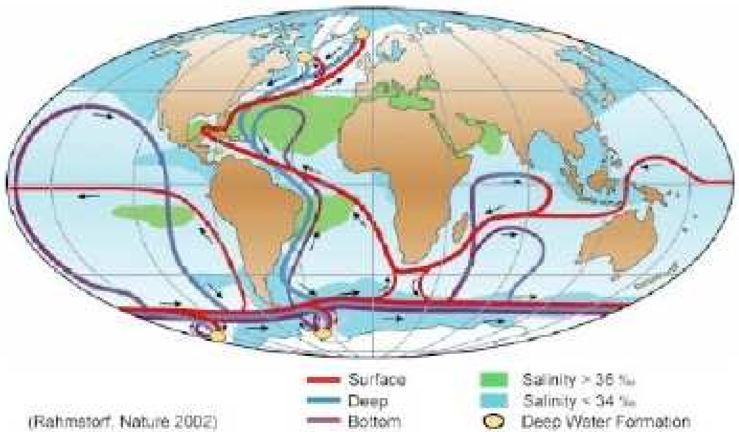
- Introduction to convection, its representation in numerical models
- A simple analytic model of convective processes
- Results for a realistic convective ensemble
- Conclusions

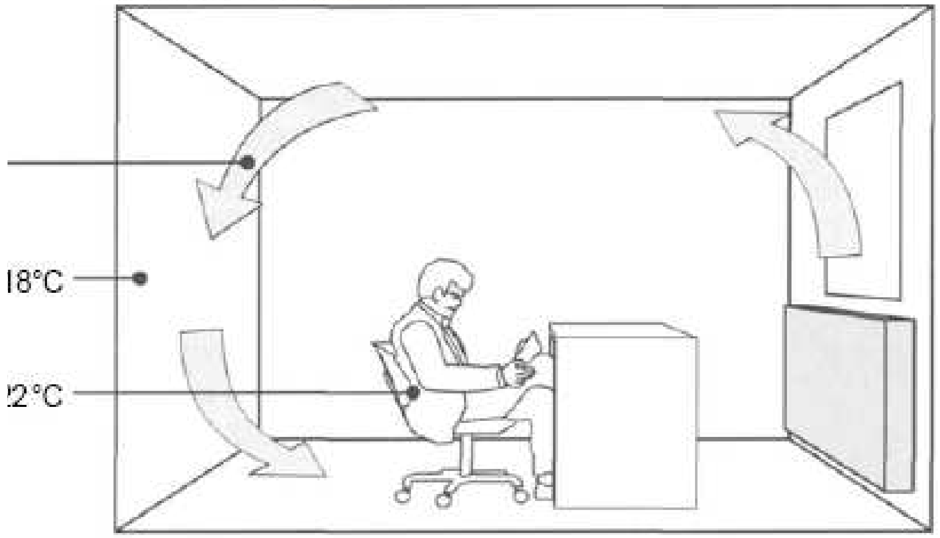
What is convection?

Convection on the web!



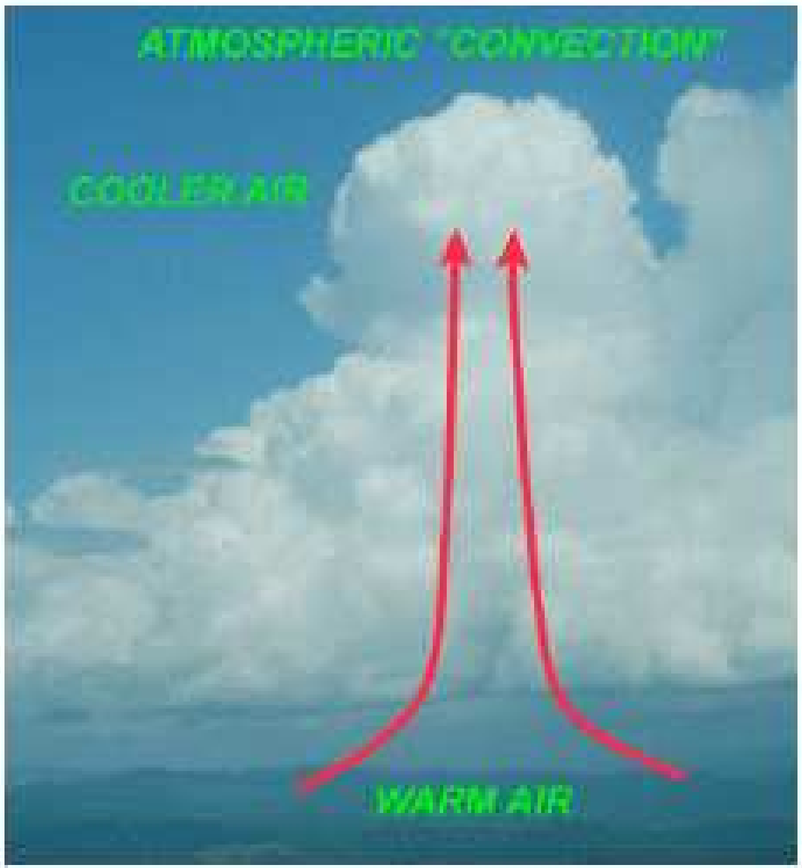


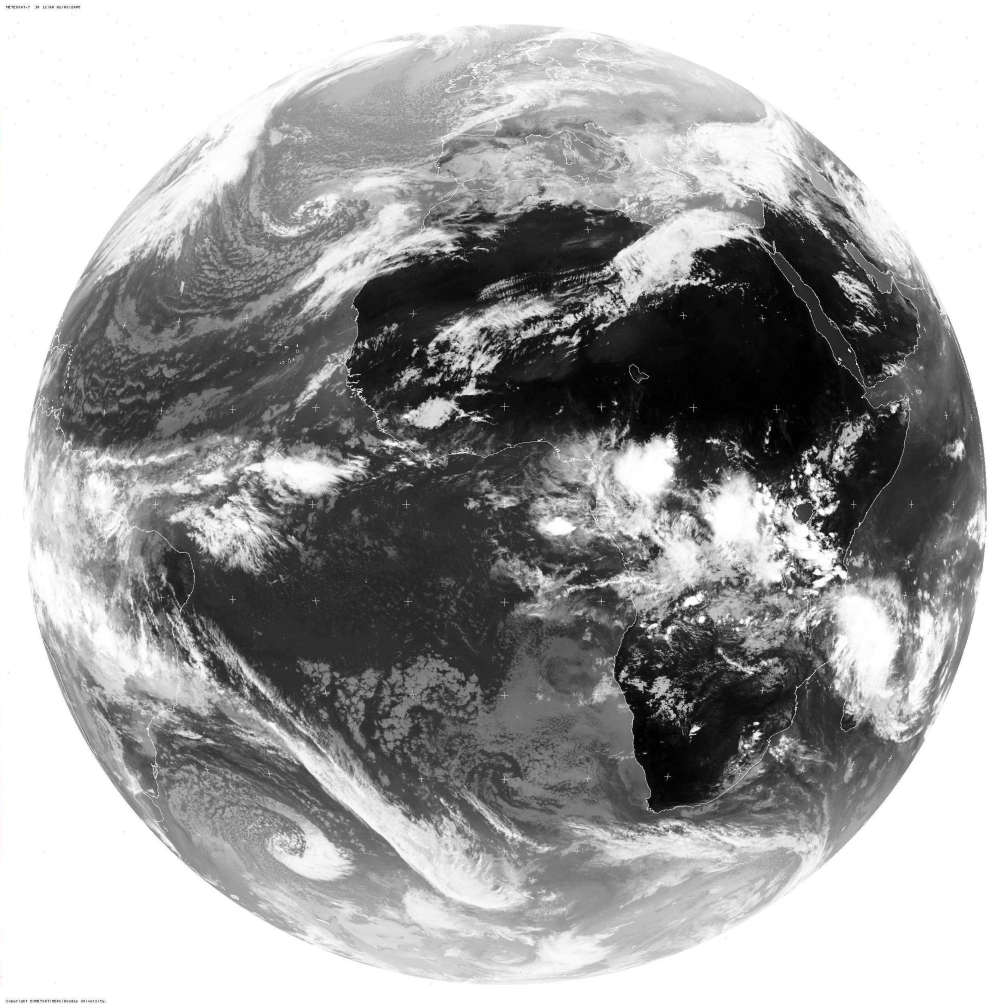




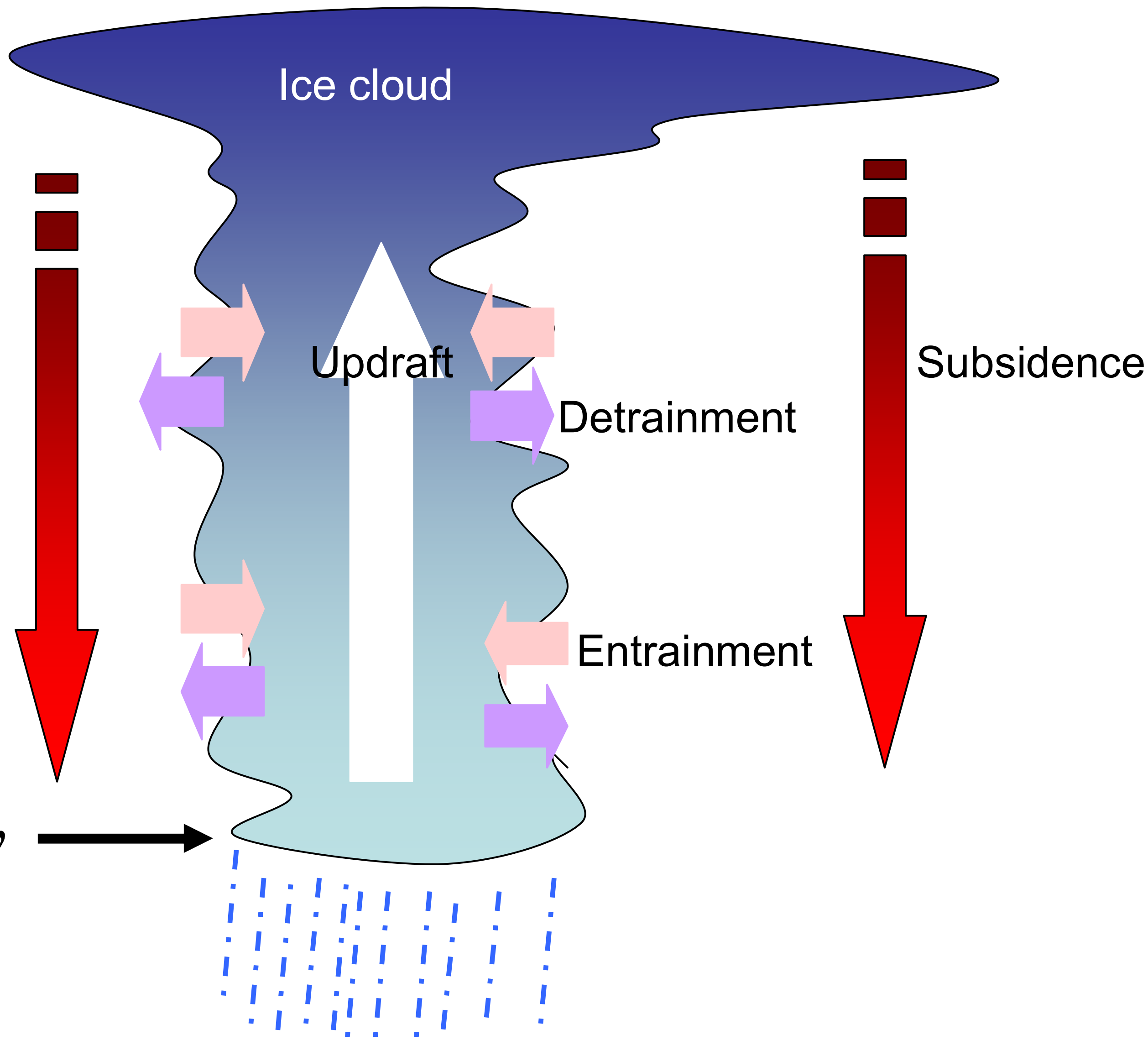
MOD report on space heating

Atmospheric convection





A convective cloud



Mass flux $= \rho A \times w$ [kg/s]

Representation of convection in numerical models

Convection meets NWP

- Convective systems are a major contributor to global circulations of heat, mass and momentum

- Representation depends on scale of model

    High resolution models explicitly resolve clouds

    Large scale models require parameterisation

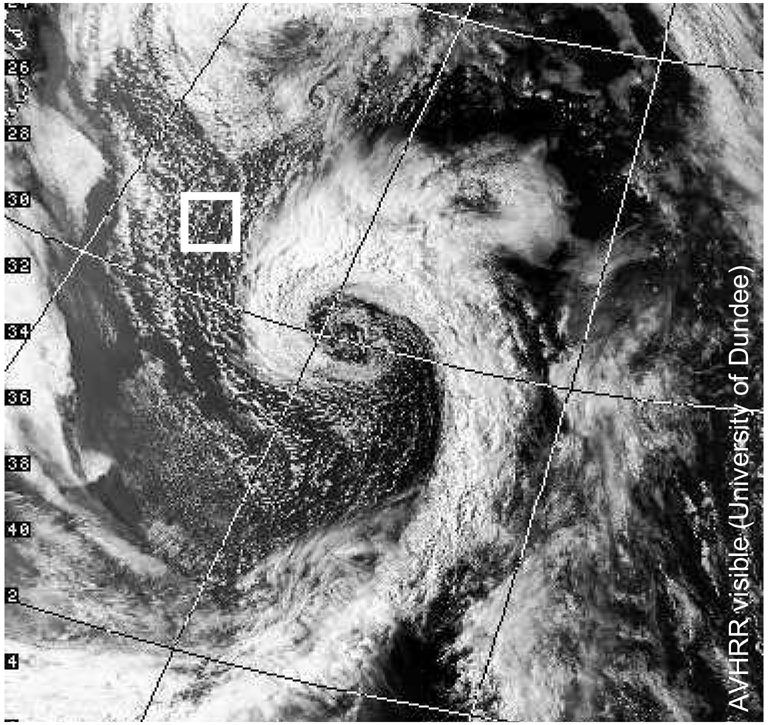
- Parameterisations represent the mean effect of the sub-grid scale cloud process on the large scale flow

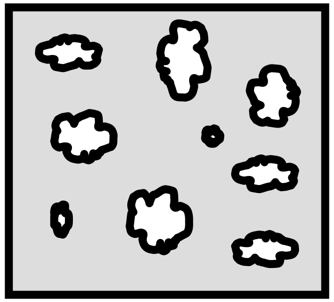
- For validity this requires assumptions to be made about the mean convection

The assumptions

- Convection acts over shorter distances and on faster timescales than the large scale flow

- Scale separation in time and space between cloud processes and large scale flow





- Convective ensemble

- Analogous to the equation of state

  $p = \rho RT$

Parameterisation basics

Arakawa and Schubert (1974)

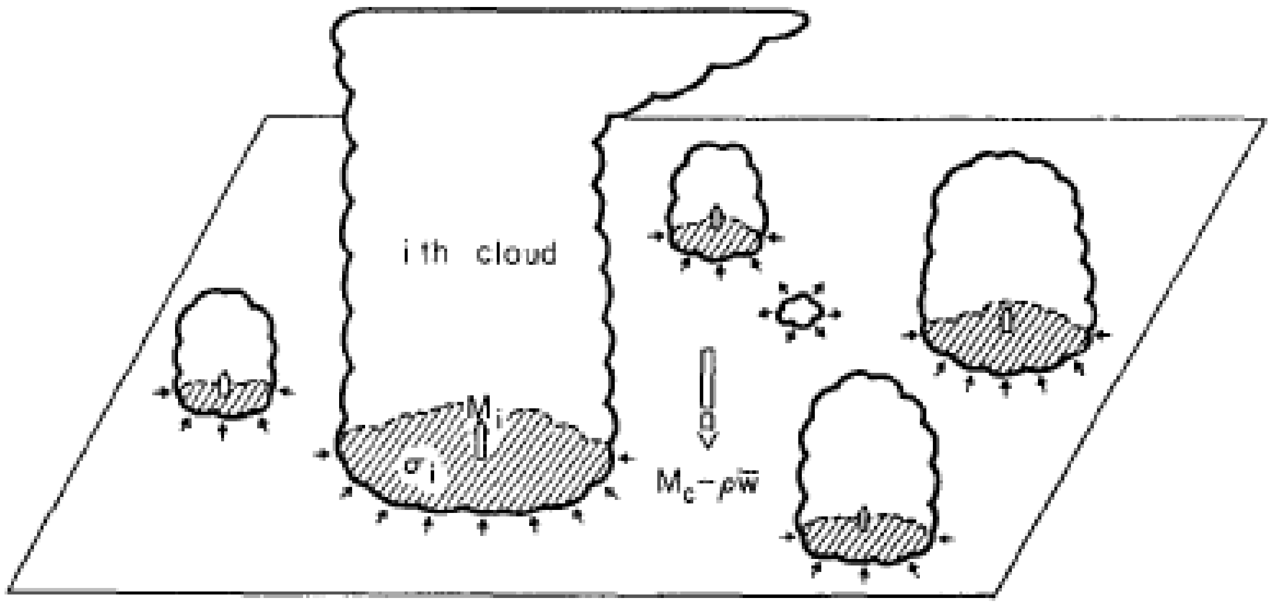


FIG. 1. A unit horizontal area at some level between cloud base and the highest cloud top. The taller clouds are shown penetrating this level and entraining environmental air. A cloud which has lost buoyancy is shown detraining cloud air into the environment.

$$\tau_{adj} \ll \tau_{ls}$$

Key equilibrium assumption

Equilibrium–an earthly analogue

Convective ensemble = sheep in field

Forcing = irrigation system

Energy in system = length of grass

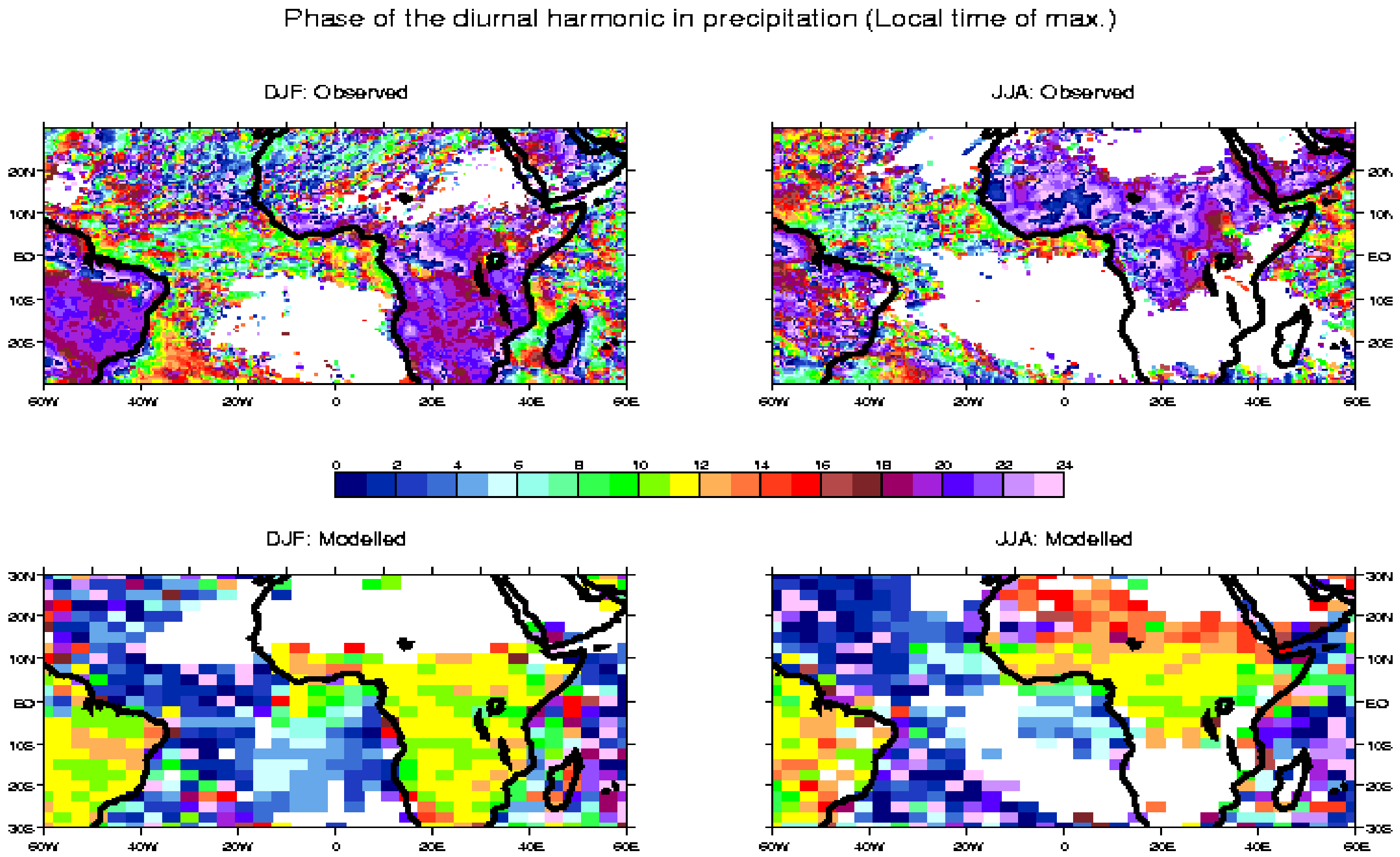
Sheep eat the grass to keep it short!

Precipitation = ??!

After Dave Randall (CSU) with thanks to Pier Siebesma (KNMI)

Motivation

- Model compared to observations (Yang & Slingo 2001)



- Longer systematic life cycle…memory?

Summary so far…

- Convective systems are a major contributor to global circulations of heat, mass and momentum.

- In large scale models convection requires parameterisation.

- Most convective parameterisations make the assumption of equilibrium.

$$\tau_{adj} \ll \tau_{ls}$$

- Observations suggest that parameterisation are failing to capture features such as the diurnal cycle.

Are these assumptions always valid?

In particular, what happens if the scale separation in time breaks down?

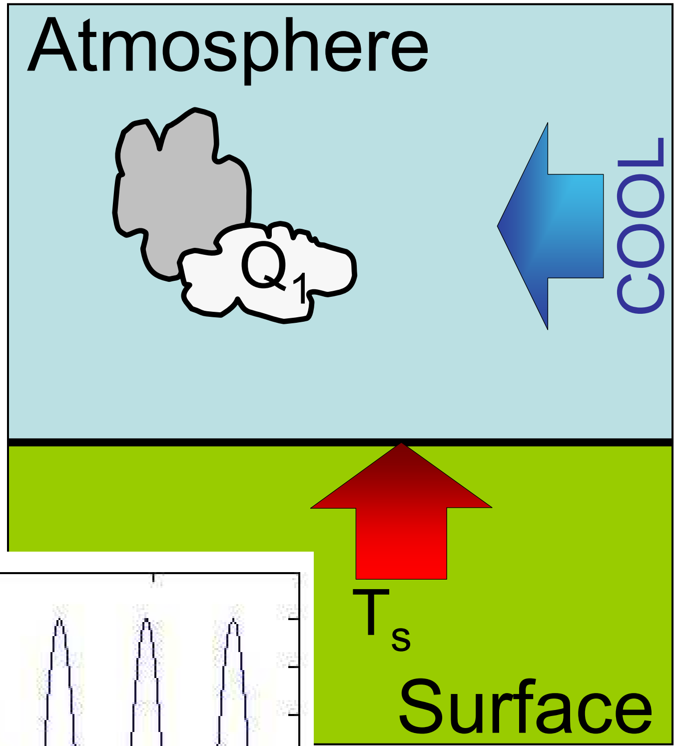
A simple analytic model of convection

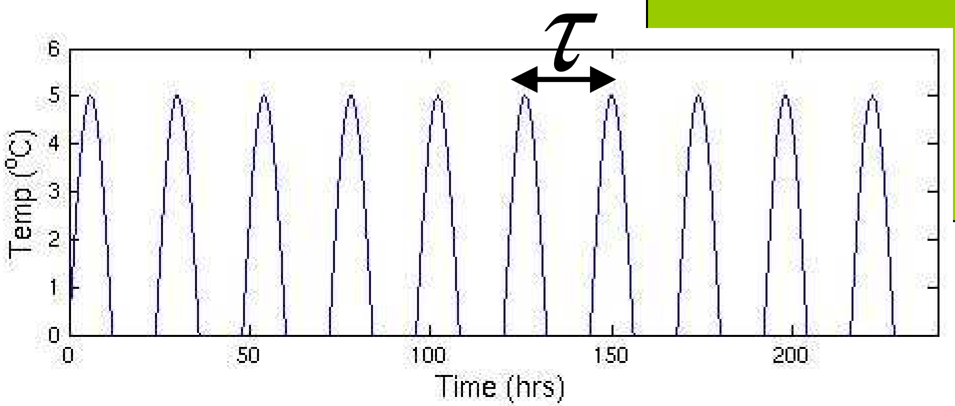
Convective memory

$$\frac{dT}{dt} = COOL + Q_1$$

$$R = \frac{T_n - T_s}{t_{close}}$$

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

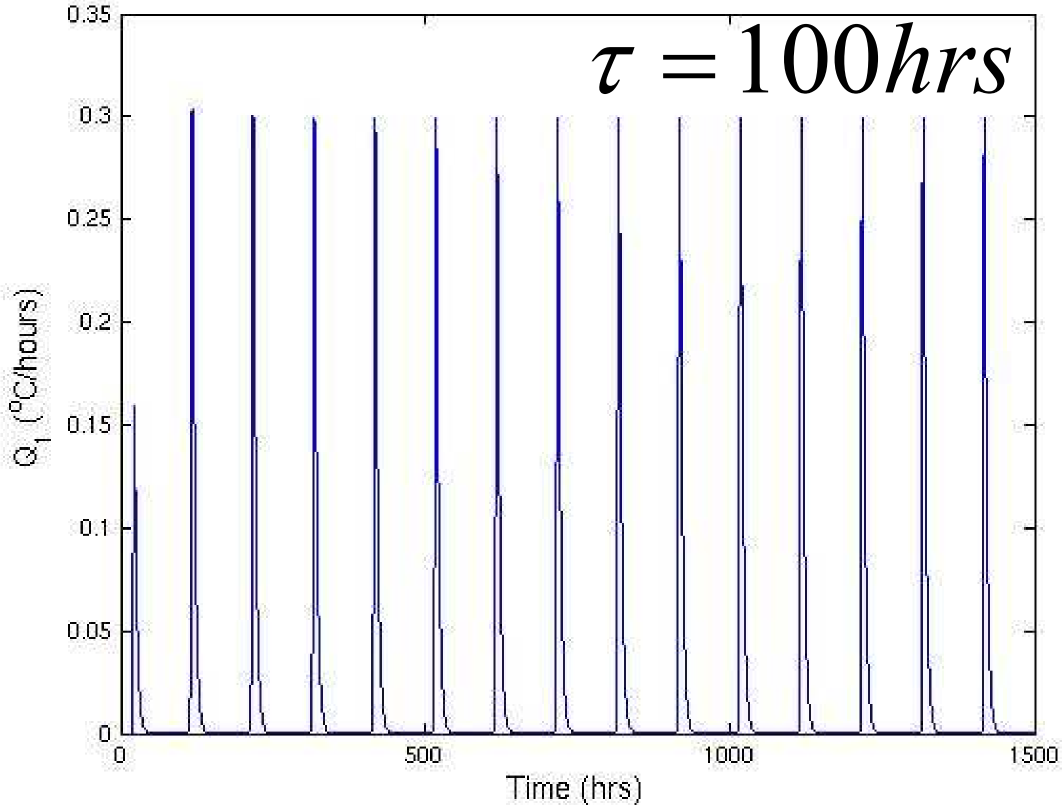




- 3 timescales t_{mem}, t_{close} and τ
- What are the characteristics of this system?

Model results

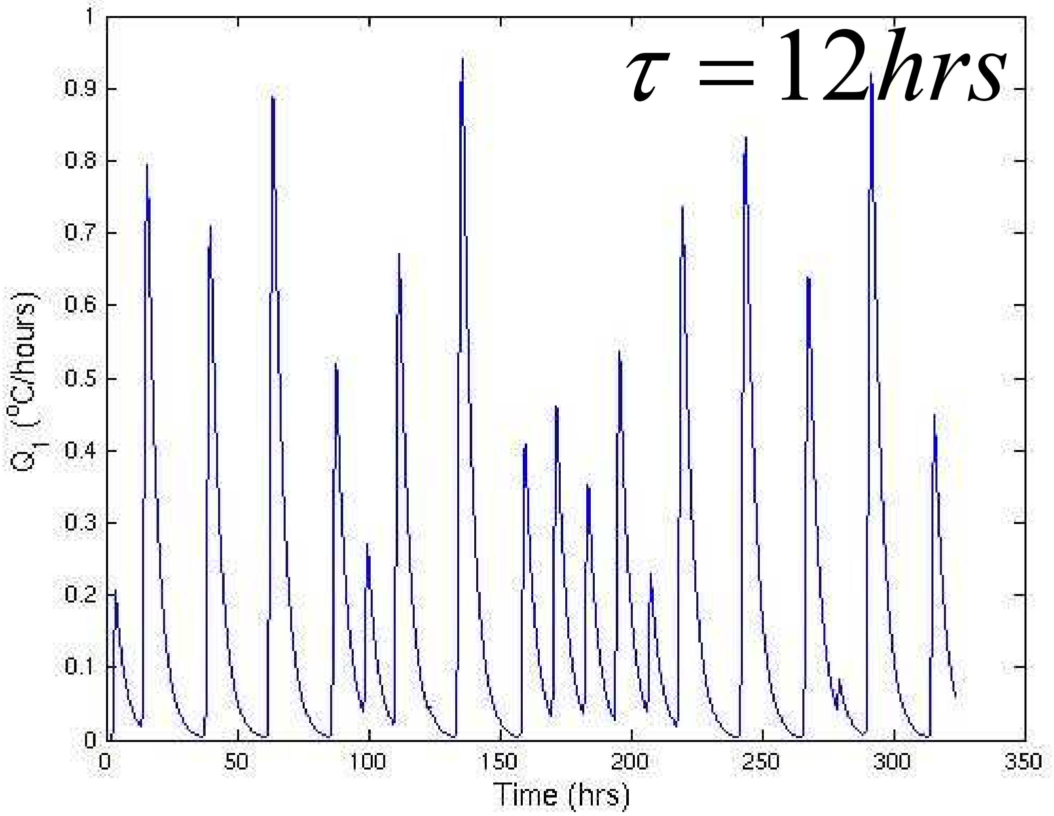
$$t_{mem} = 4hrs \quad t_{close} = 0.5hrs$$



Response repetitive and 'matches' forcing.

Model results

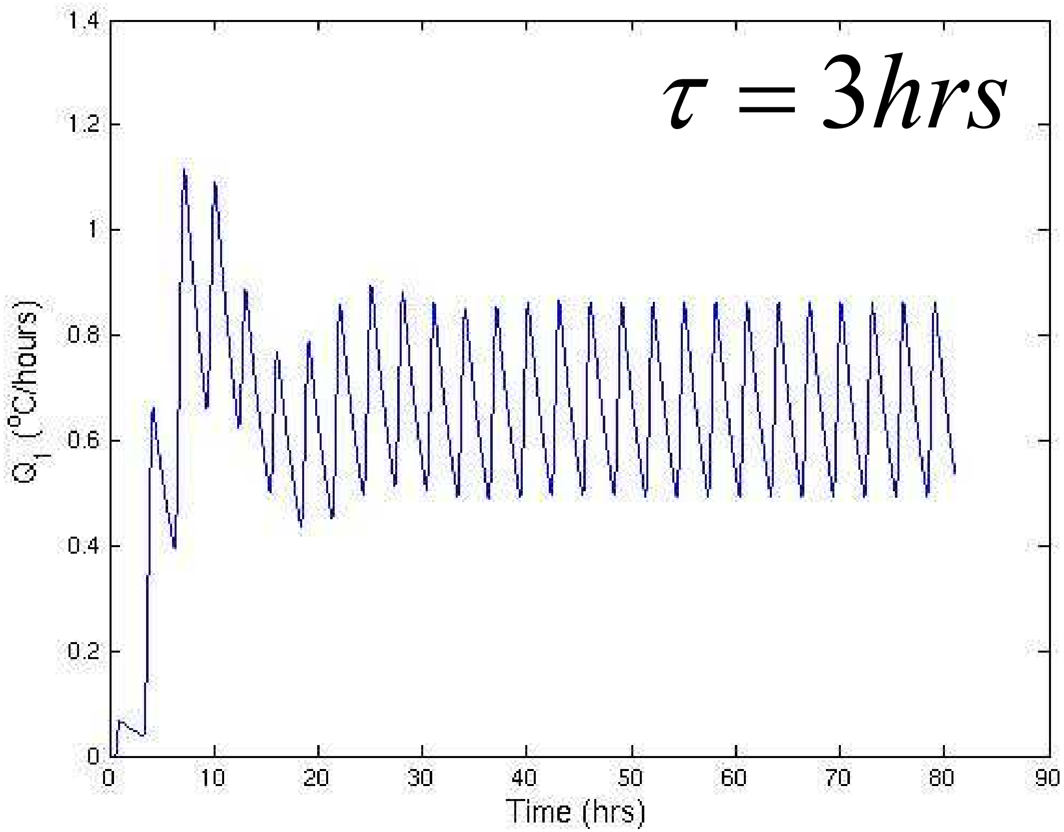
$$t_{mem} = 4hrs \quad t_{close} = 0.5hrs$$



Response not repetitive and not obviously linked with forcing.

Model results

$$t_{mem} = 4hrs \quad t_{close} = 0.5hrs$$



Response repetitive but convection tends to constant value with fluctuations about mean.

Summary so far…

- A simple analytic model, with a memory timescale, shows that the characteristics of the response depend on the forcing timescale.
- When the forcing timescale is close to the memory timescale the response is not solely related to the current forcing – there is feedback.
- In a convective system, the current amount of convection is dependant on the time-history of the convection.

Can we observe these characteristics for realistic convection?

For what timescales is there feedback in the system?

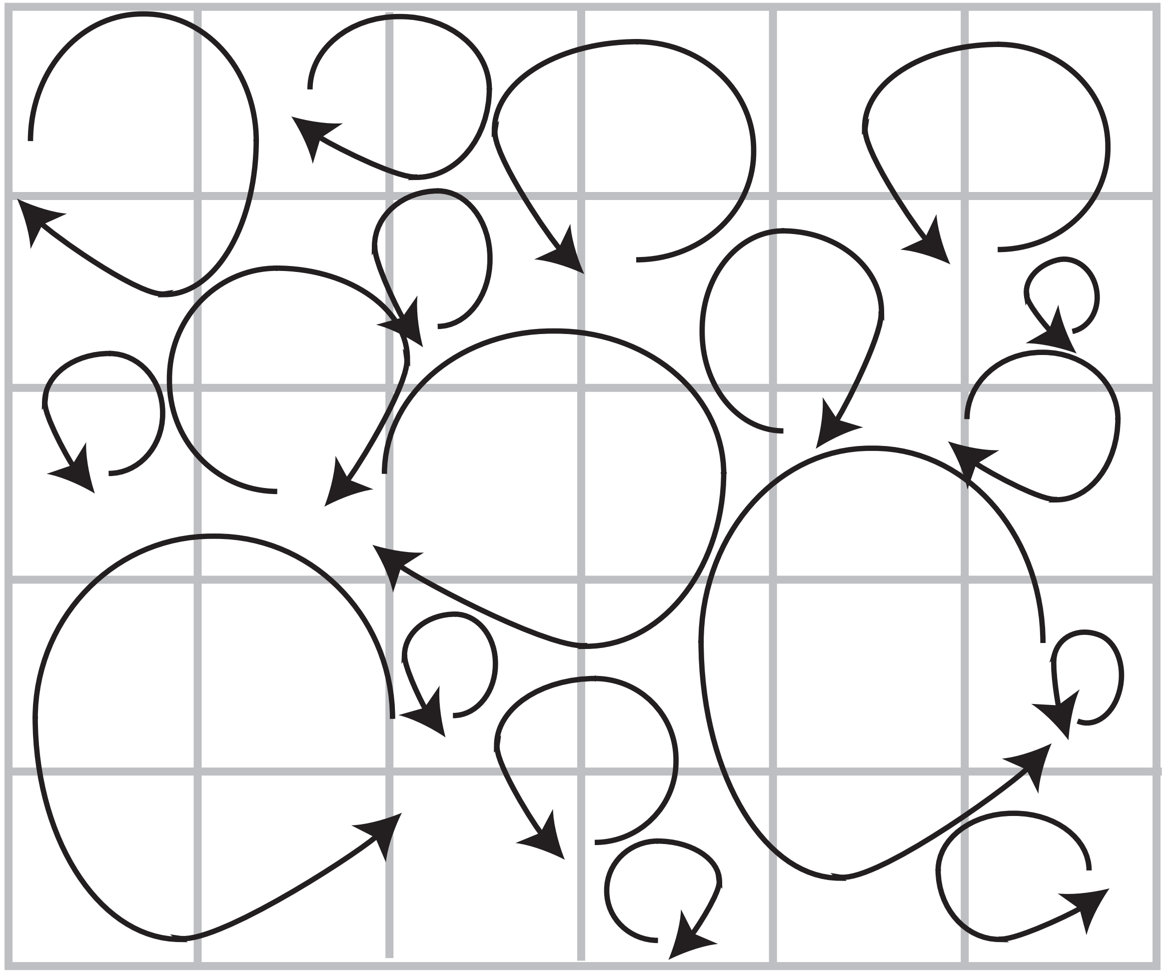
Convection in a realistic convective ensemble

Large eddy models (1)

- LEM run as a cloud resolving model explicitly resolves cloud-scale dynamics but parameterises sub-grid processes.

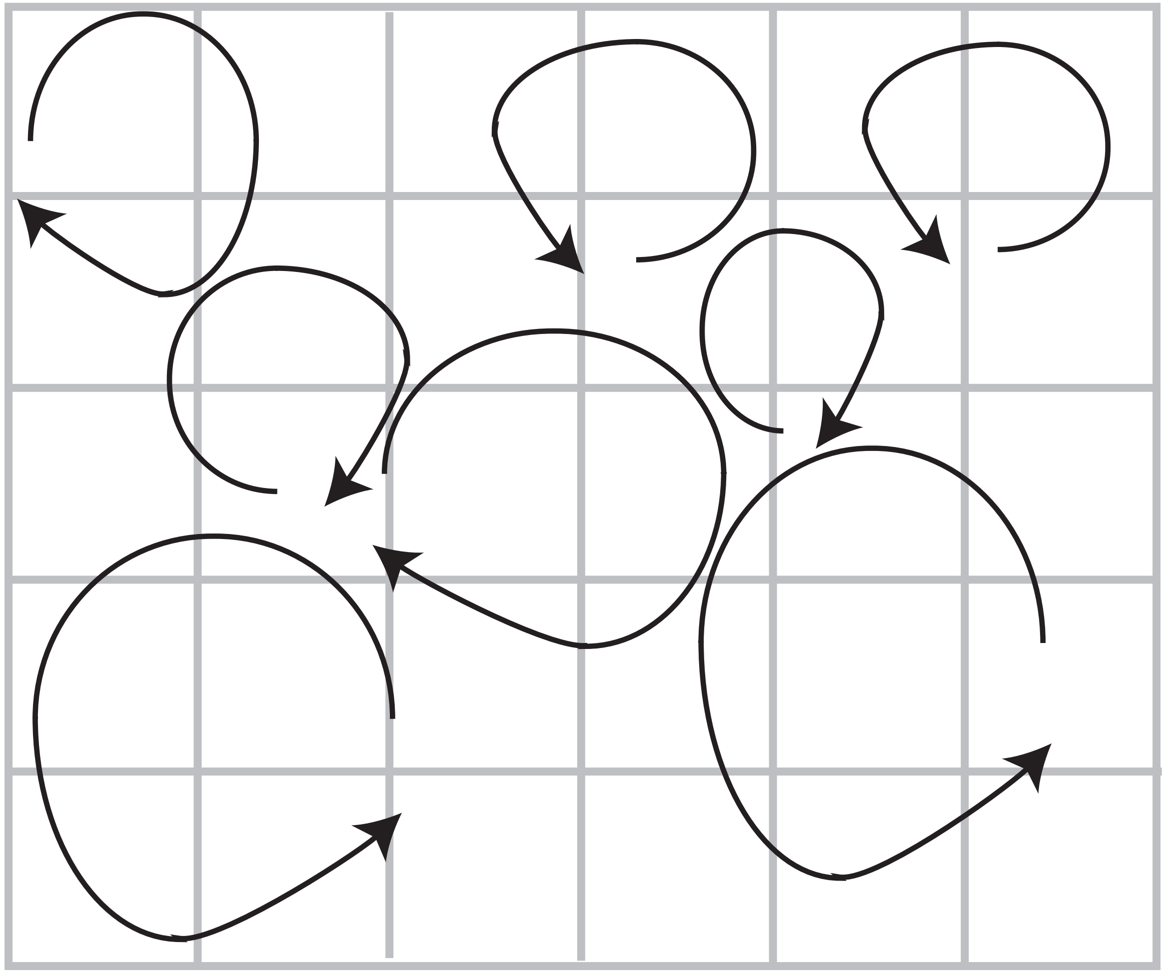
- Largest eddies are responsible for majority of transport so are explicitly resolved.

Large eddy models (2)



Full field - as in direct numerical simulation

Large eddy models (3)



Large eddy resolved field – ideal for convection

Large eddy models (4)

- LEM run as a cloud resolving model explicitly resolves cloud-scale dynamics but parameterises sub-grid processes.
- Largest eddies are responsible for majority of transport so are explicitly resolved.
- Used to investigate the properties of cloud ensembles for parameterisation development and GCM testing.
- Often forced with observations from field campaigns.
- Used to complement observations.

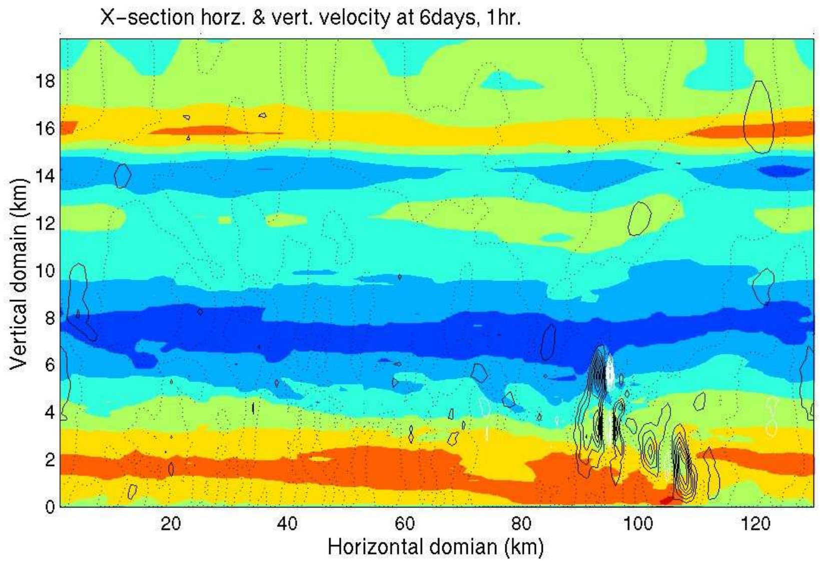
Large eddy models setup 2

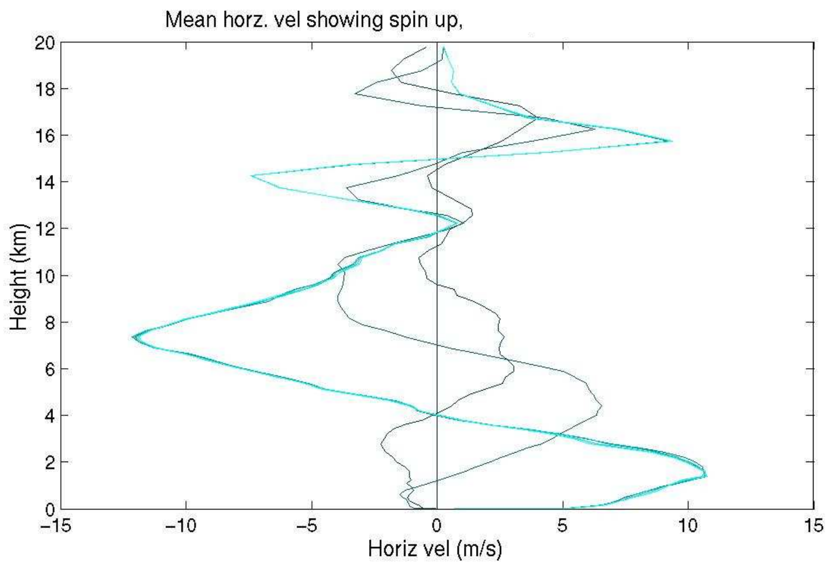
- Initialised with profiles of θ and q_v (wind speeds possible too).

- Specify Coriolis parameter, vertical profiles of wind shear.
  Neither of these.

- 2D or 3D

2 D test run





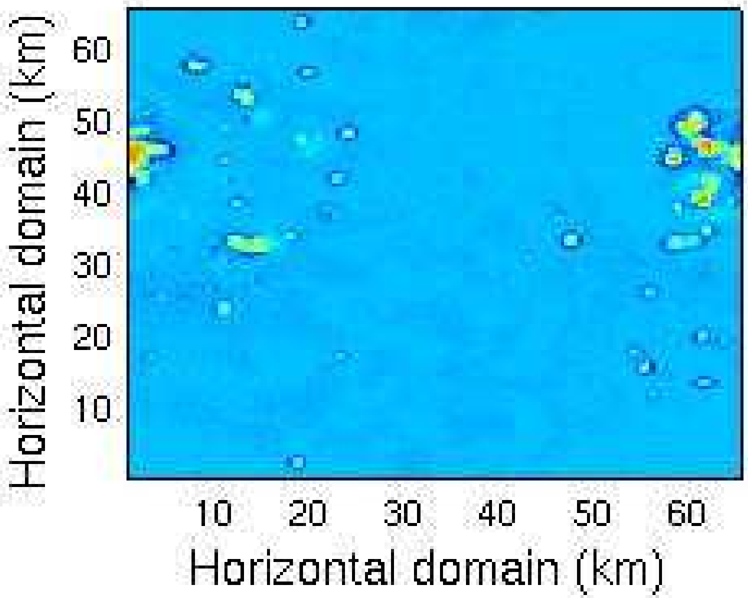
- With no imposed winds the model develops strong near surface winds.
- The motion of the convective cells is controlled by the large scale winds.
- Increasing wind shear due to insufficient damping in eddy transport compared to 3D (Mapes and Wu 2001).

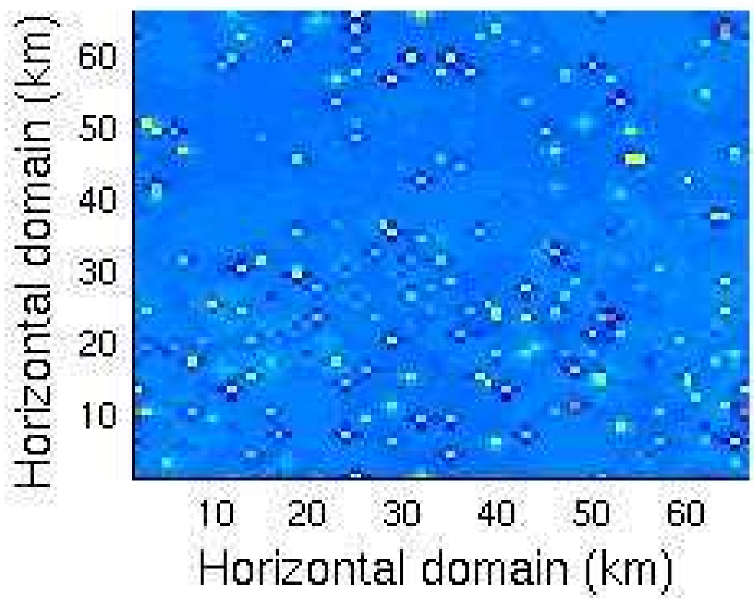
Large eddy models setup

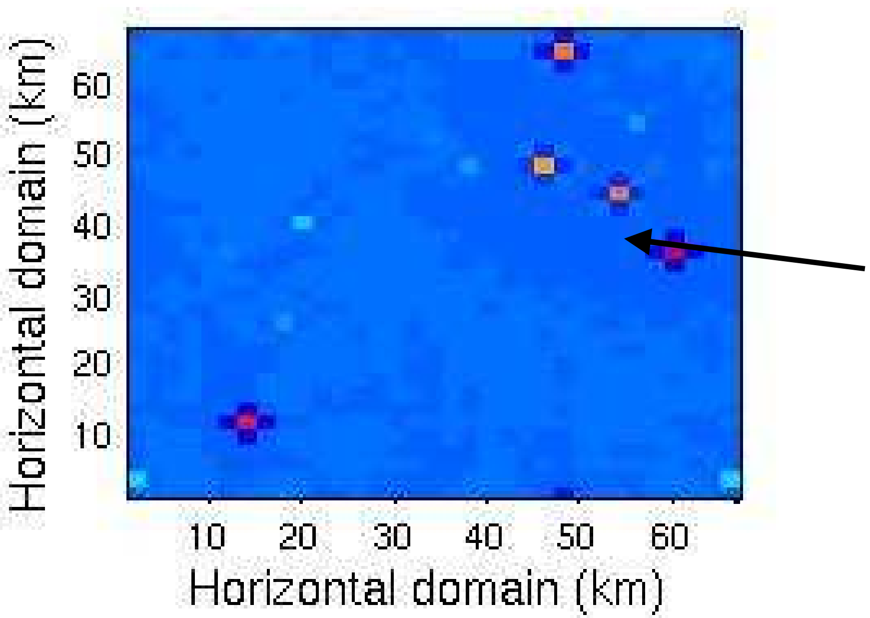
- Initialised with profiles of θ and q_v (wind speeds possible too).

- Specify Coriolis parameter, vertical profiles of wind shear.
  Neither of these.
- 2D or 3D
  3D
- Resolution

Horizontal resolution







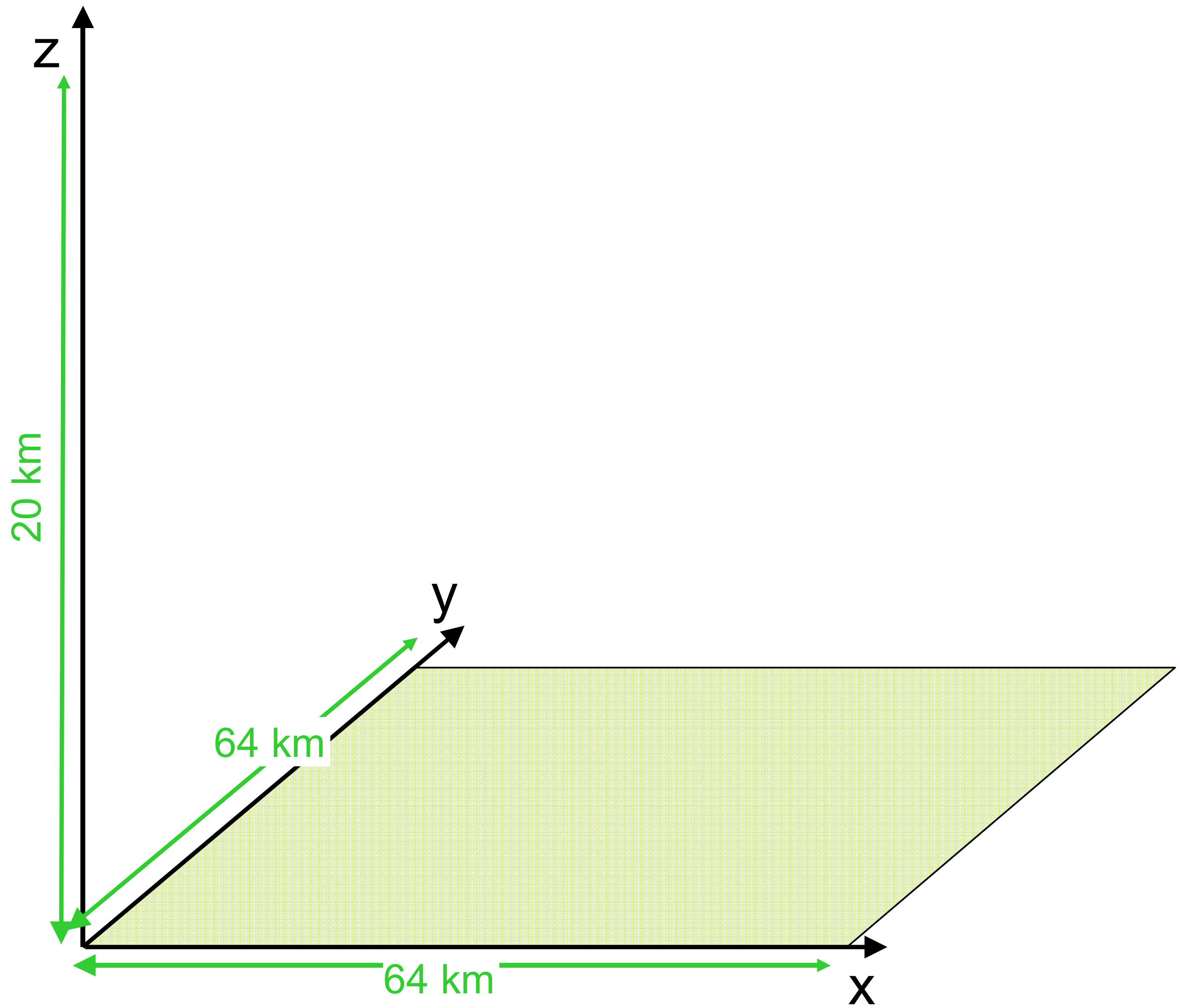
Few, isolated grip point storms modify the convective response.

Large eddy models setup 2

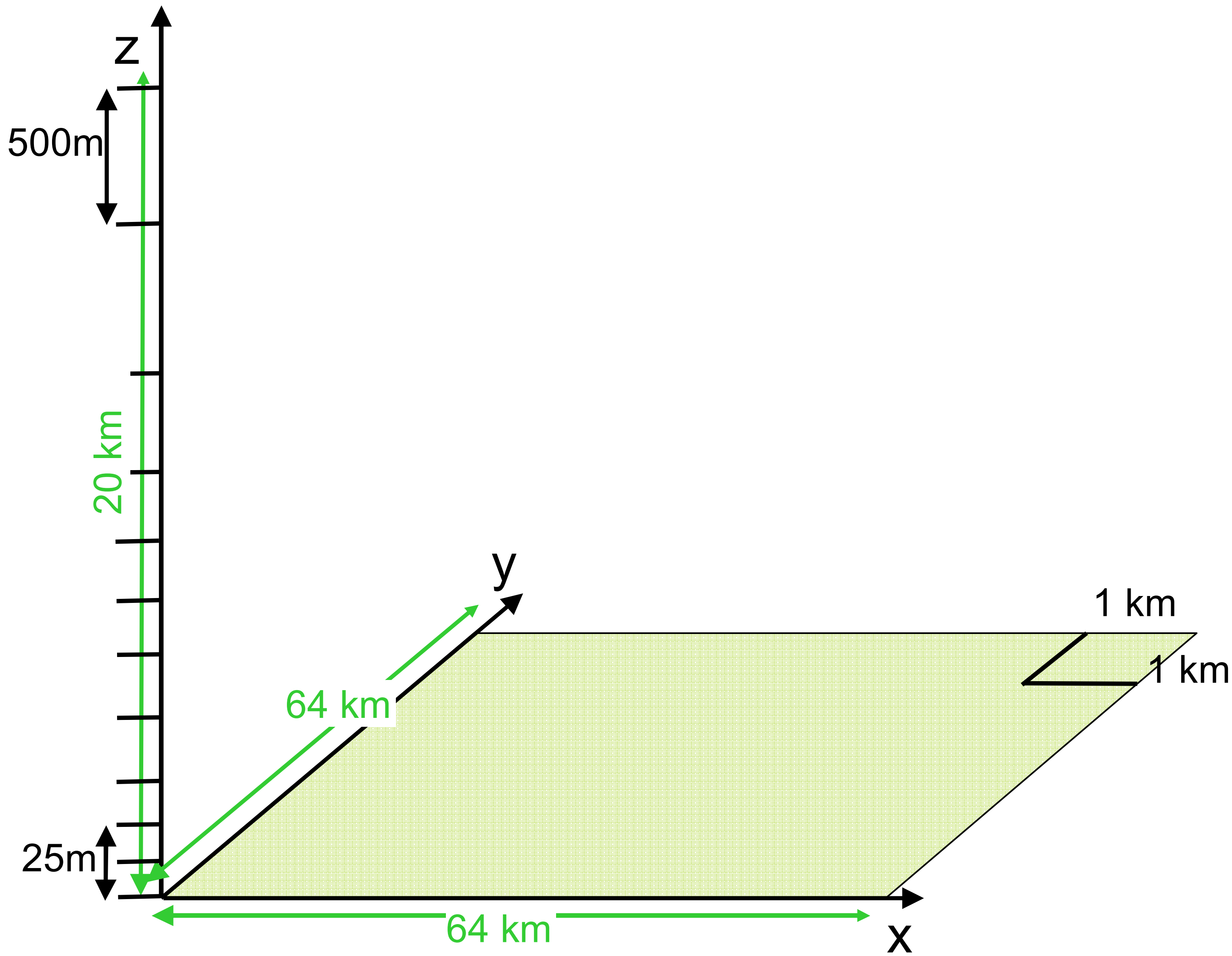
- Initialised with profiles of θ and q_v (wind speeds possible too).

- Specify Coriolis parameter, vertical profiles of wind shear.
  Neither of these.
- 2D or 3D
  3D
- Resolution
  1 km
- Large scale heating/cooling.
  Large scale cooling
- Large scale convergence.
  Nope
- Specify forcing mechanism.

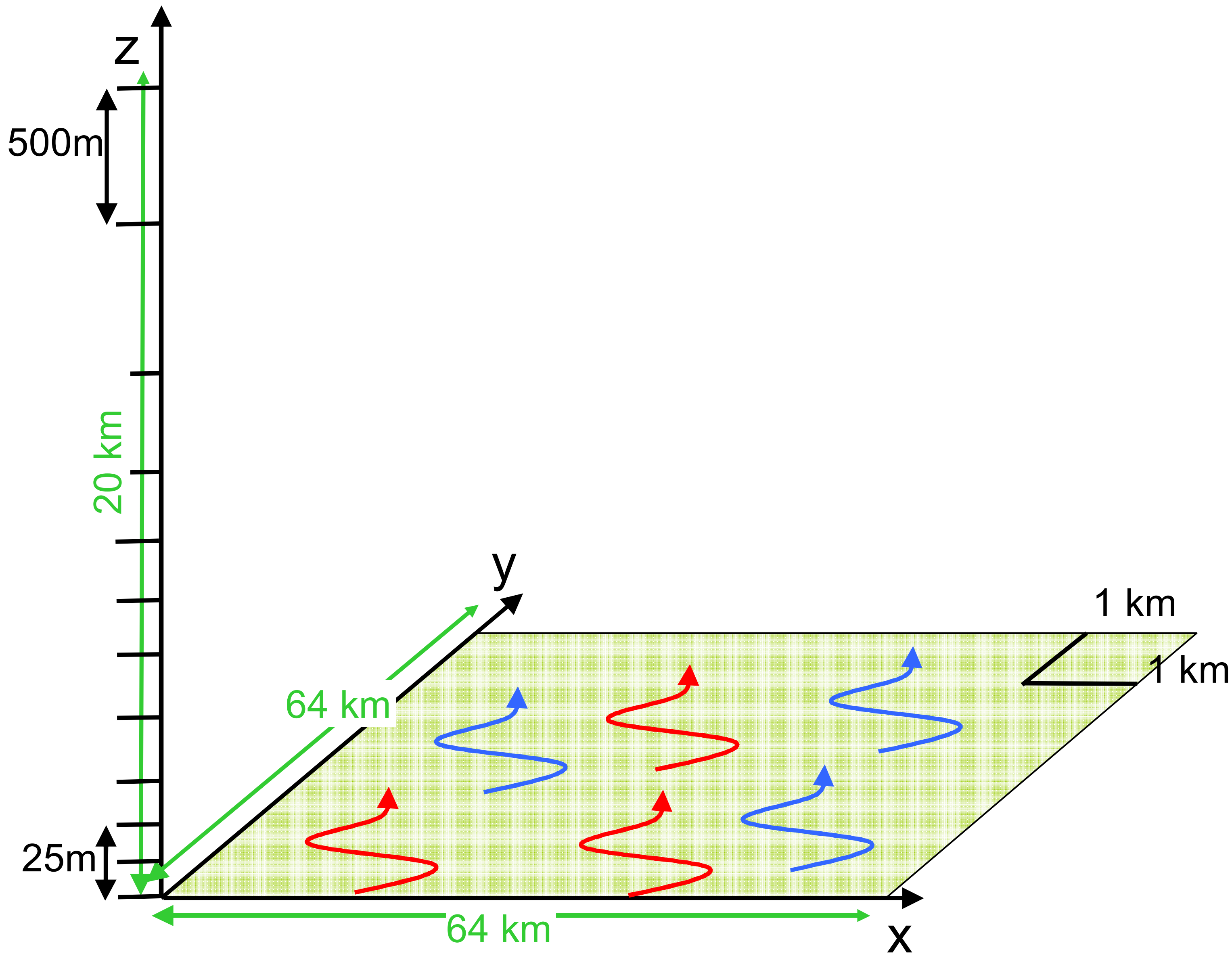
Model setup



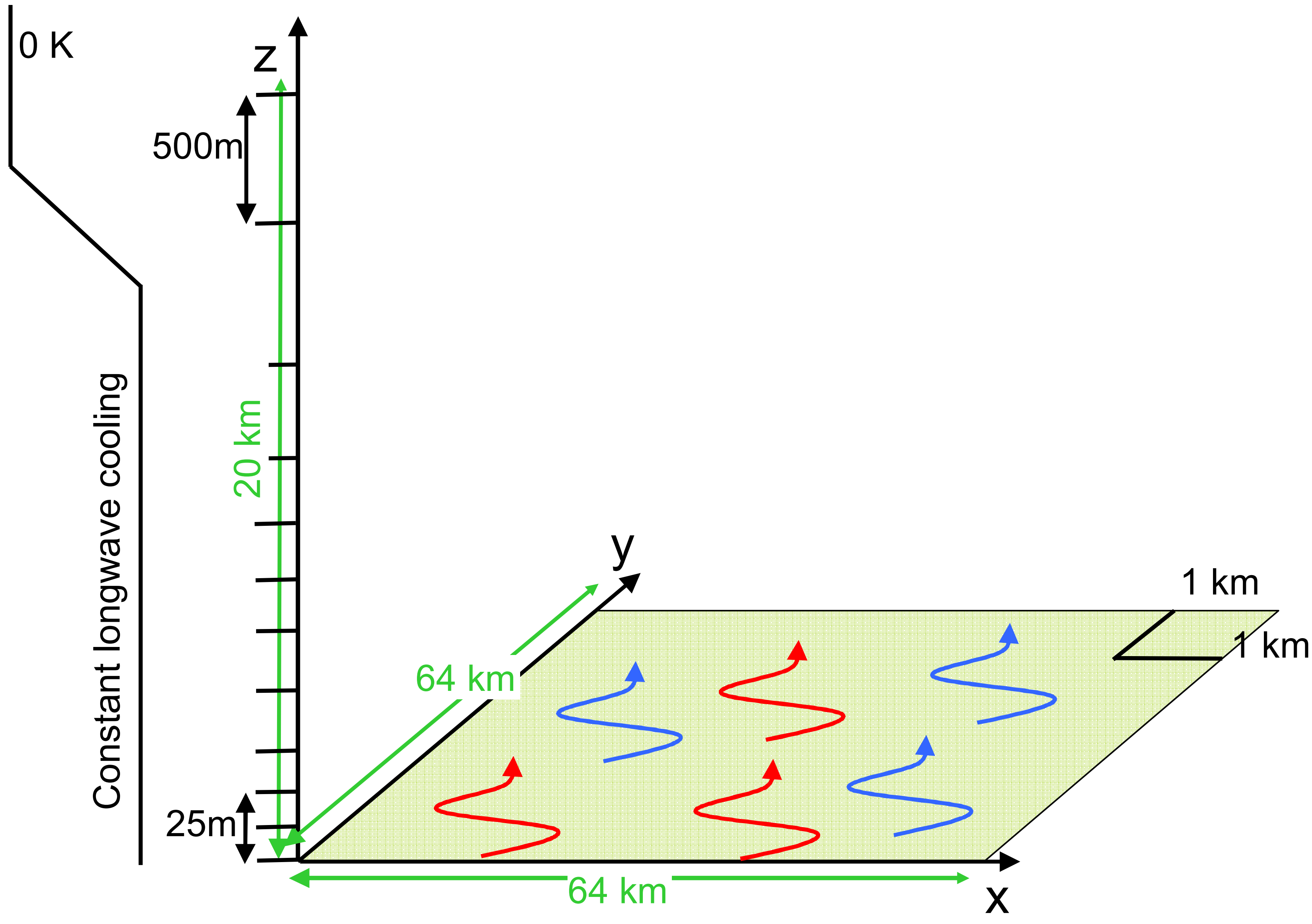
Model setup



Model setup

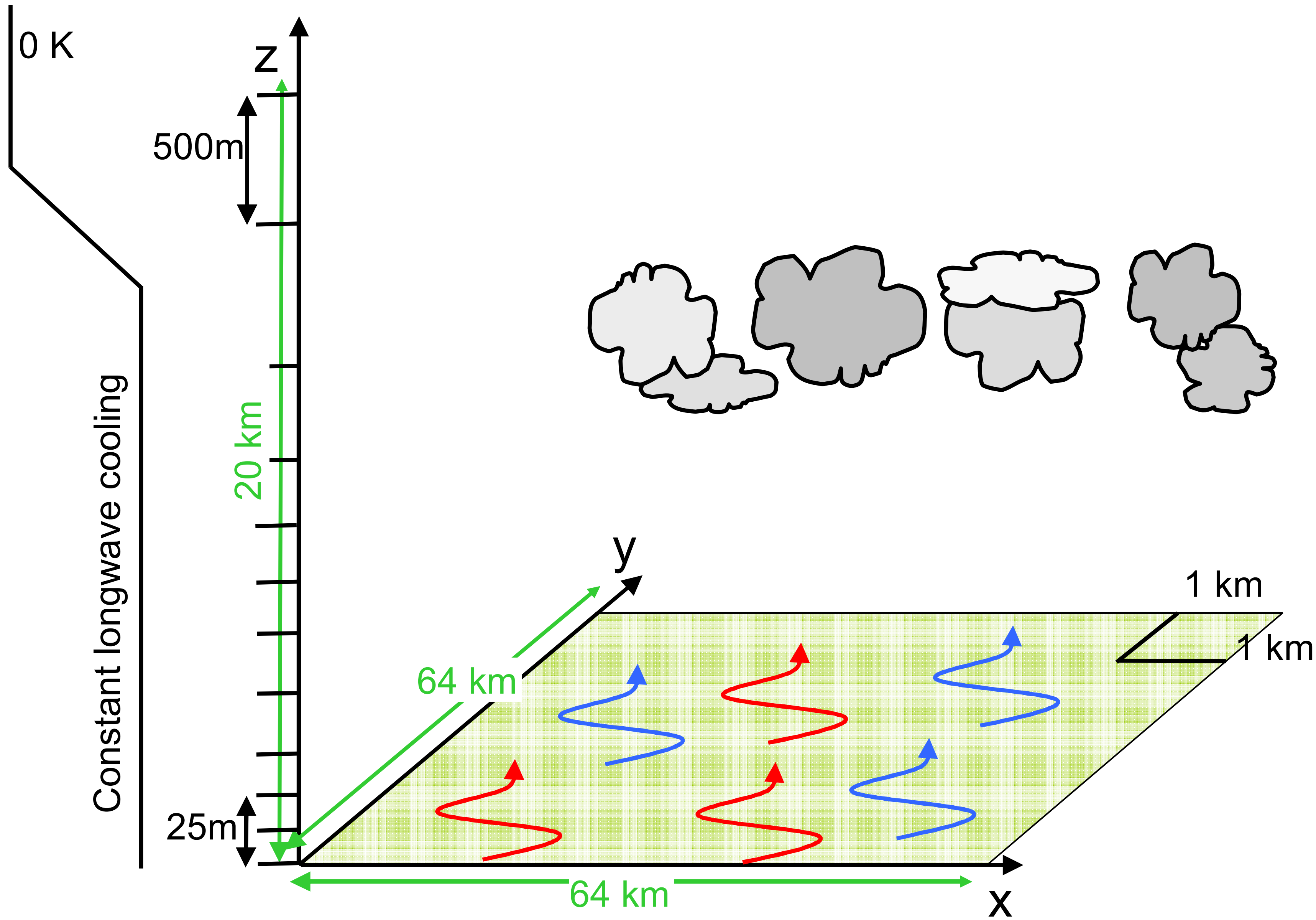


Model setup



0 K
Constant longwave cooling
z
500m
20 km
25m
y
64 km
1 km
1 km
64 km
x

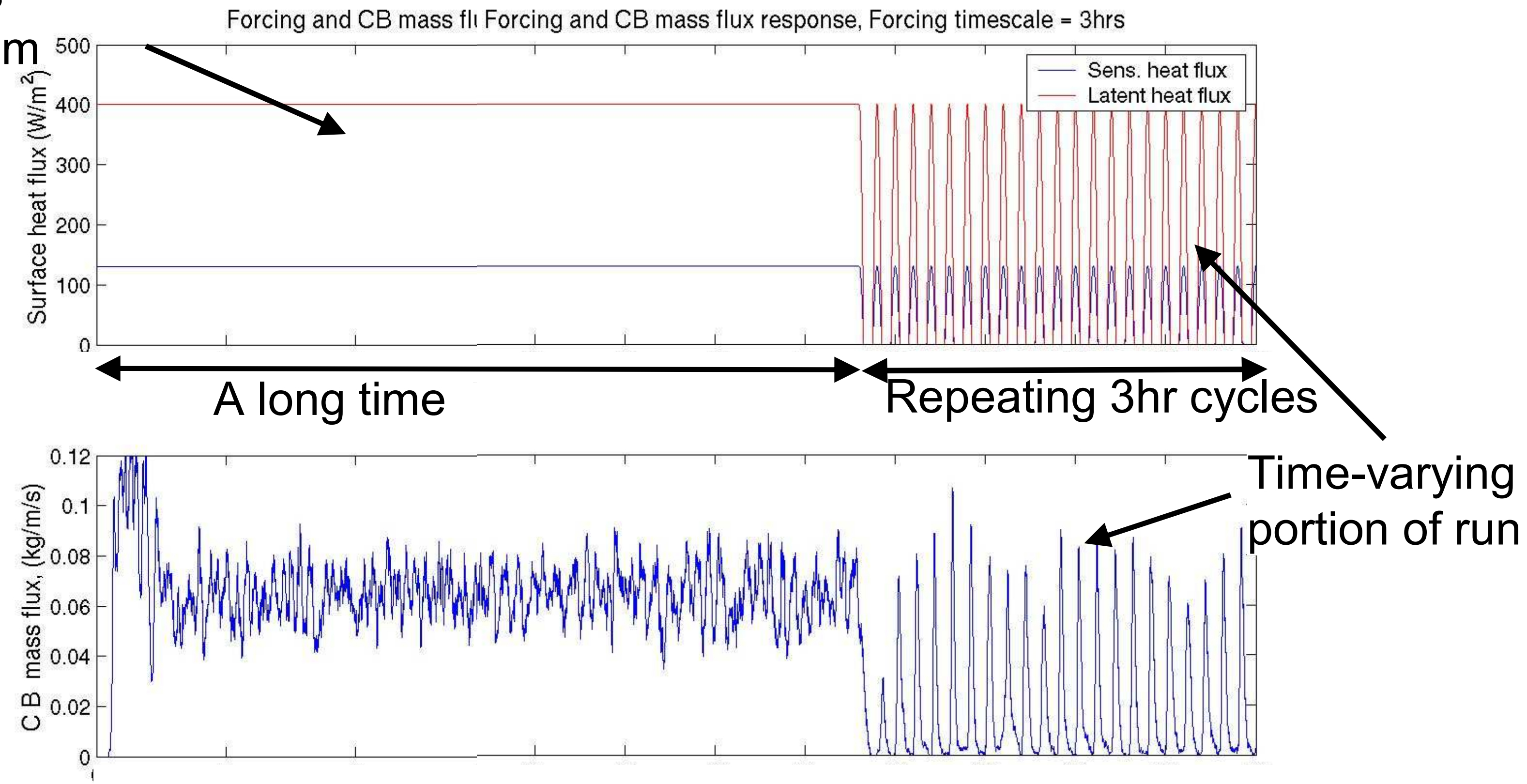
Model setup



0 K
Constant longwave cooling
z
500m
20 km
25m
y
64 km
1 km
1 km
64 km
x

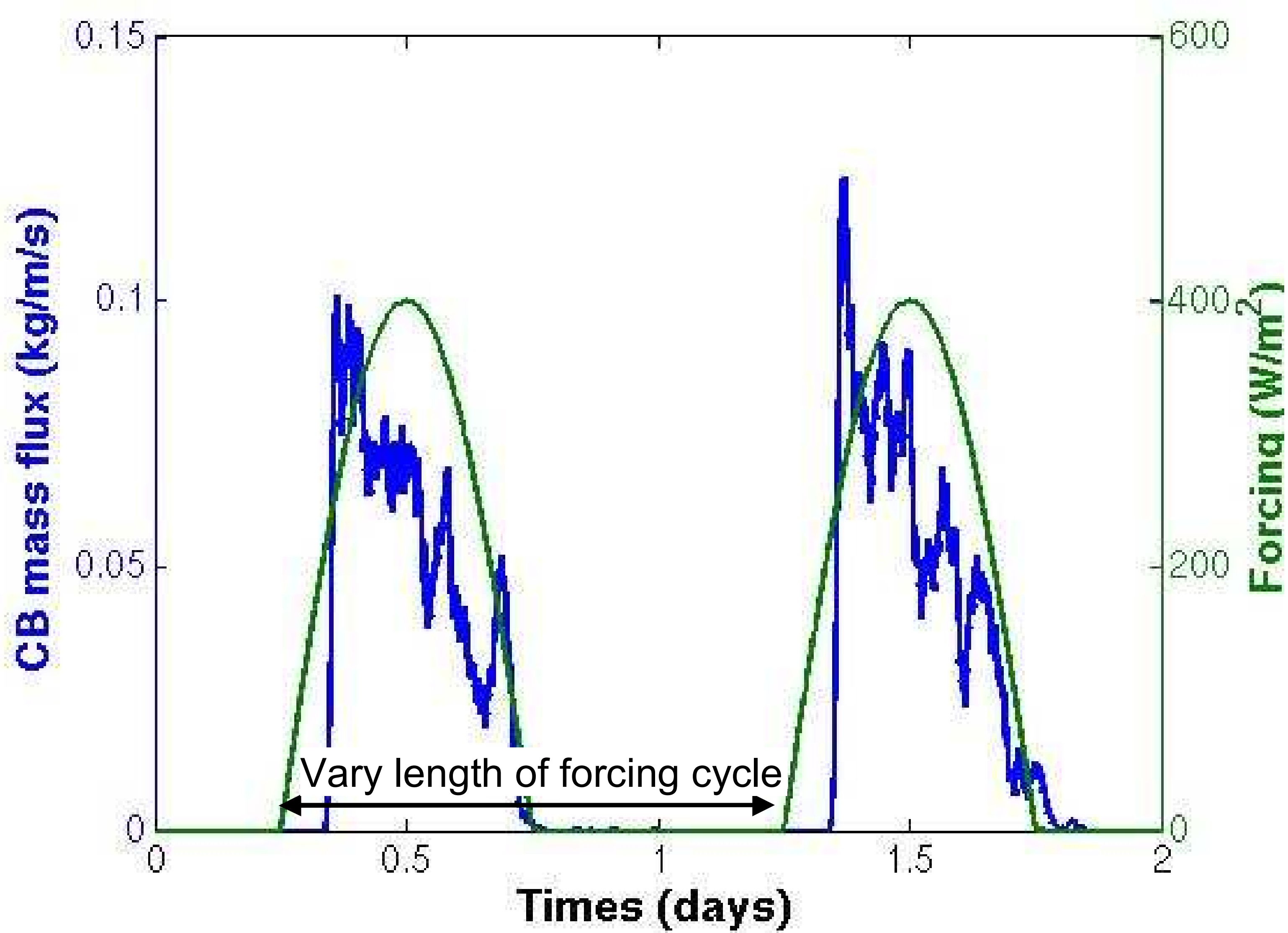
Control run

Control run:
Applying constant surface fluxes until equilibrium achieved



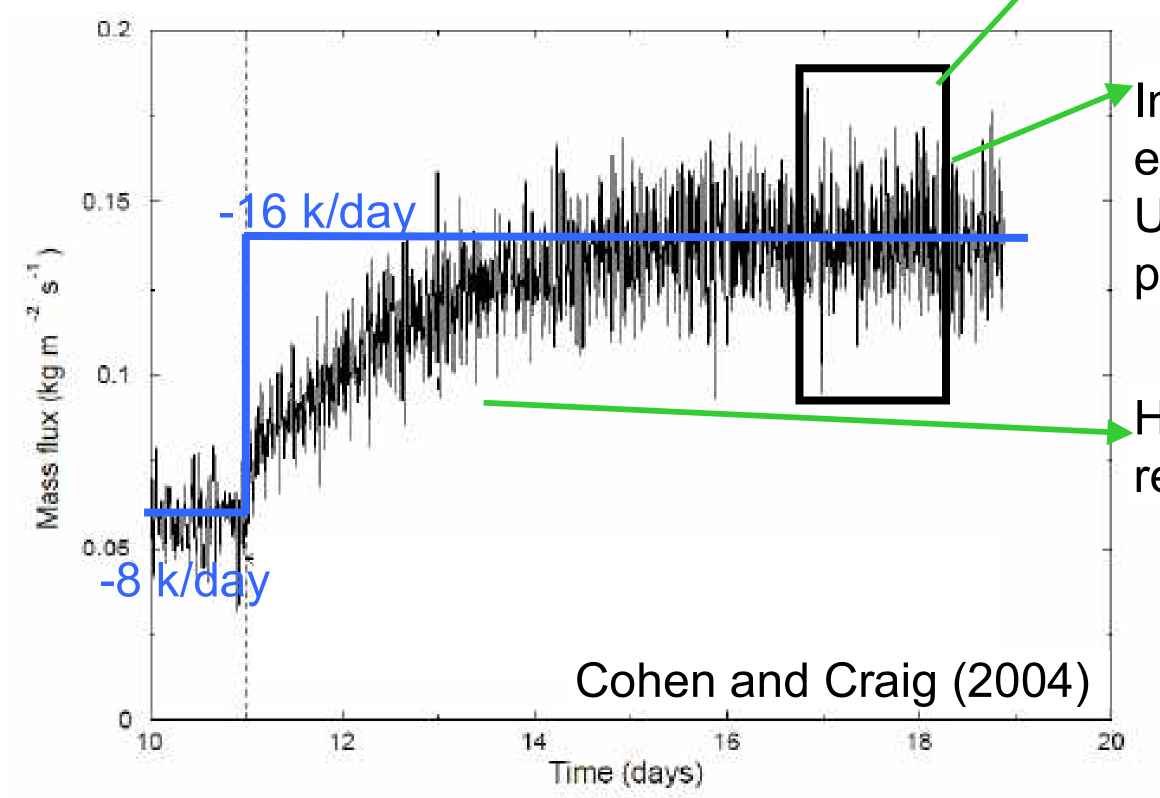
Initial convective response is strongly influenced by the control run. It was found a portion of ~ 6hrs need to be removed. This suggests 'memory' within the system.

Forcing method



RCE in LEM

- What people have done before…constant SST and longwave cooling.



Look at fluctuations – how close is the system to being in equilibrium?

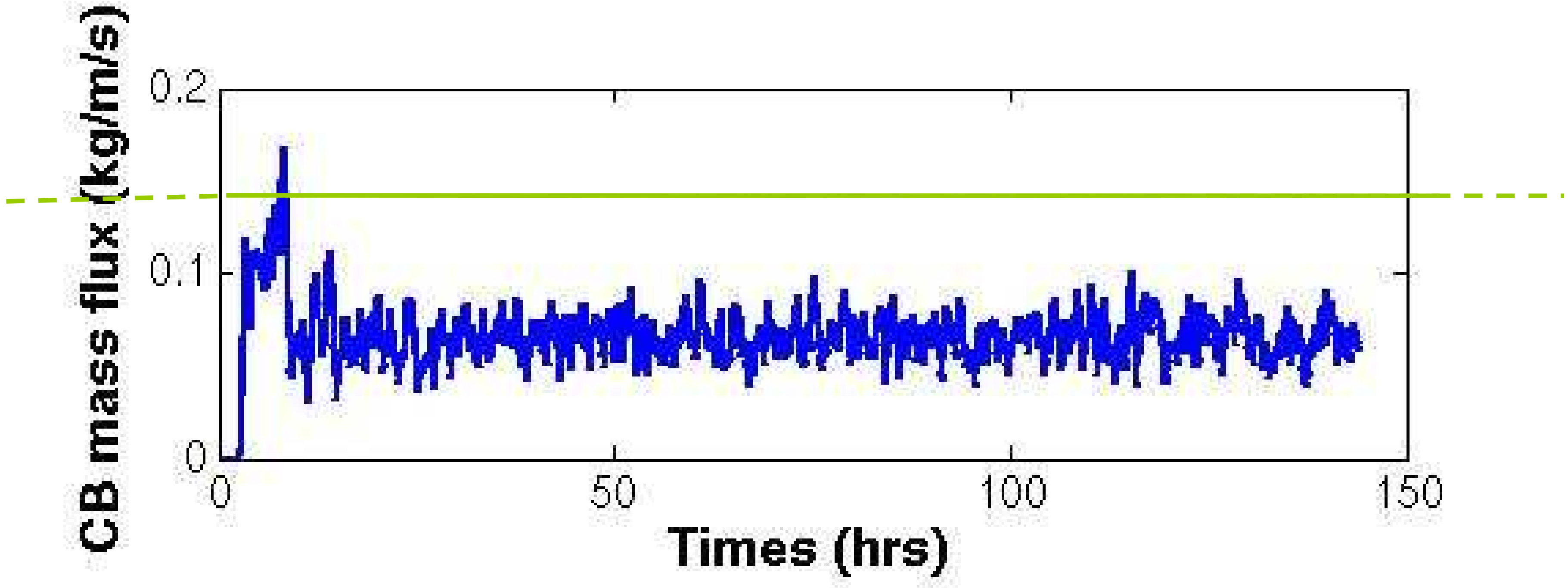
Investigate characteristics at equilibrium.
Use to motivate changes to parameterisations.

How long does it take the system to reach equilibrium?

Defining equilibrium

A working definition

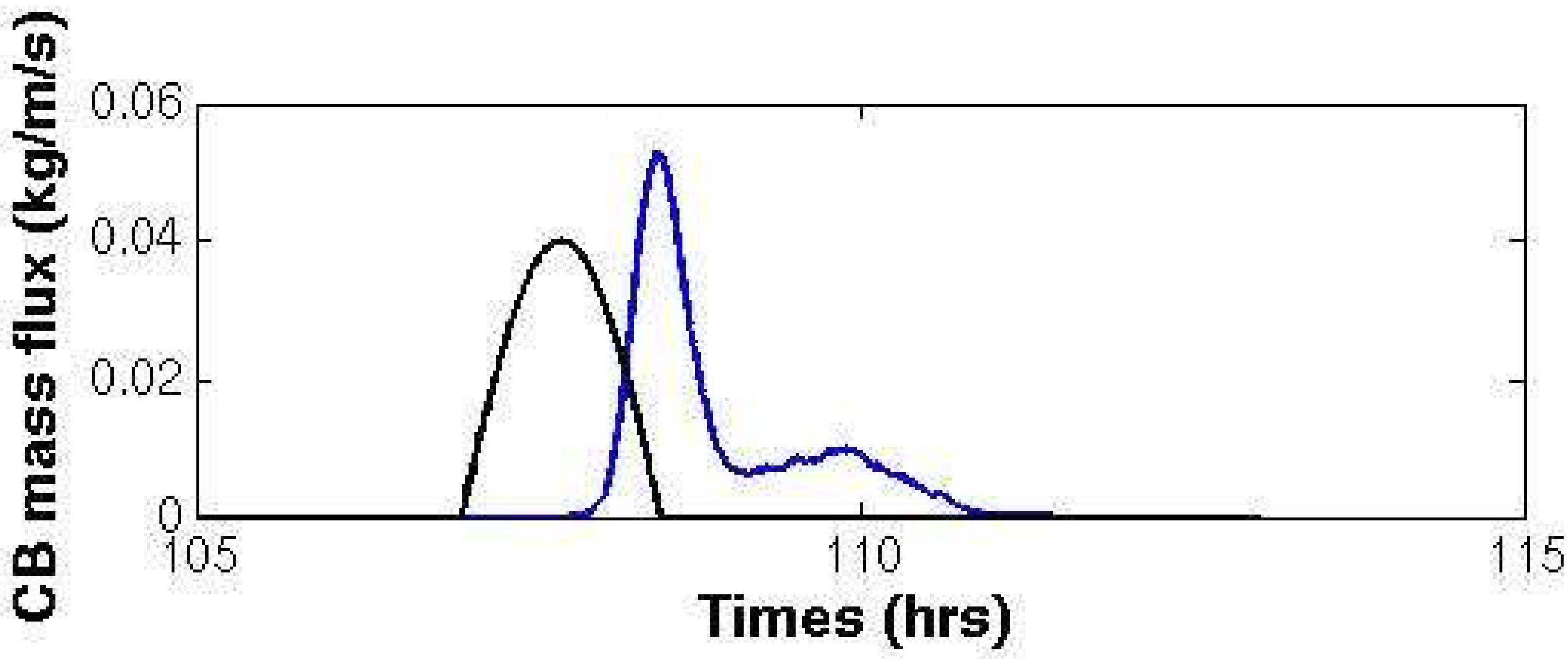
- Consider an infinitely long forcing.
- The system develops a mean amount of convection and achieves equilibrium.



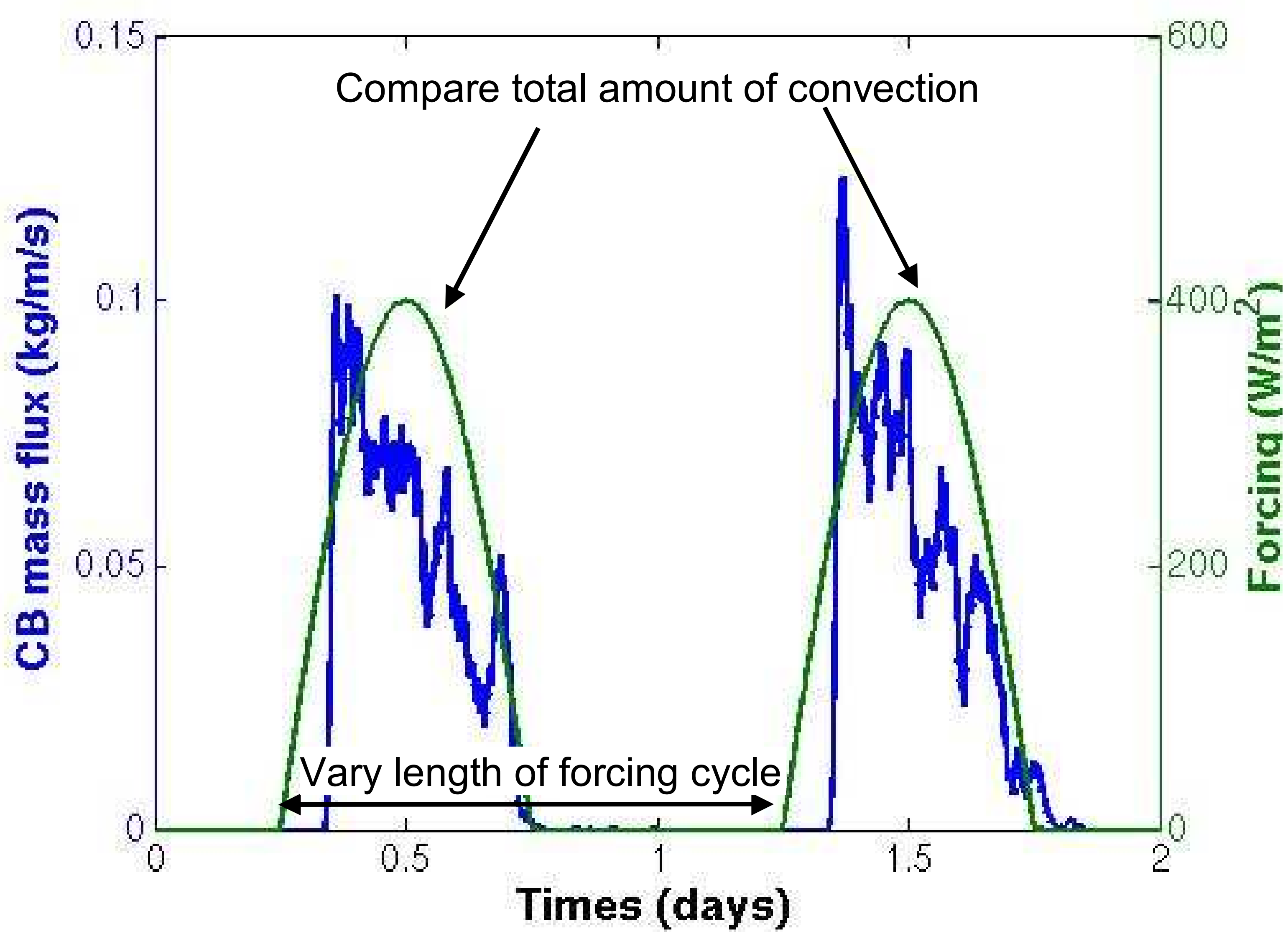
Defining equilibrium (2)

A working definition

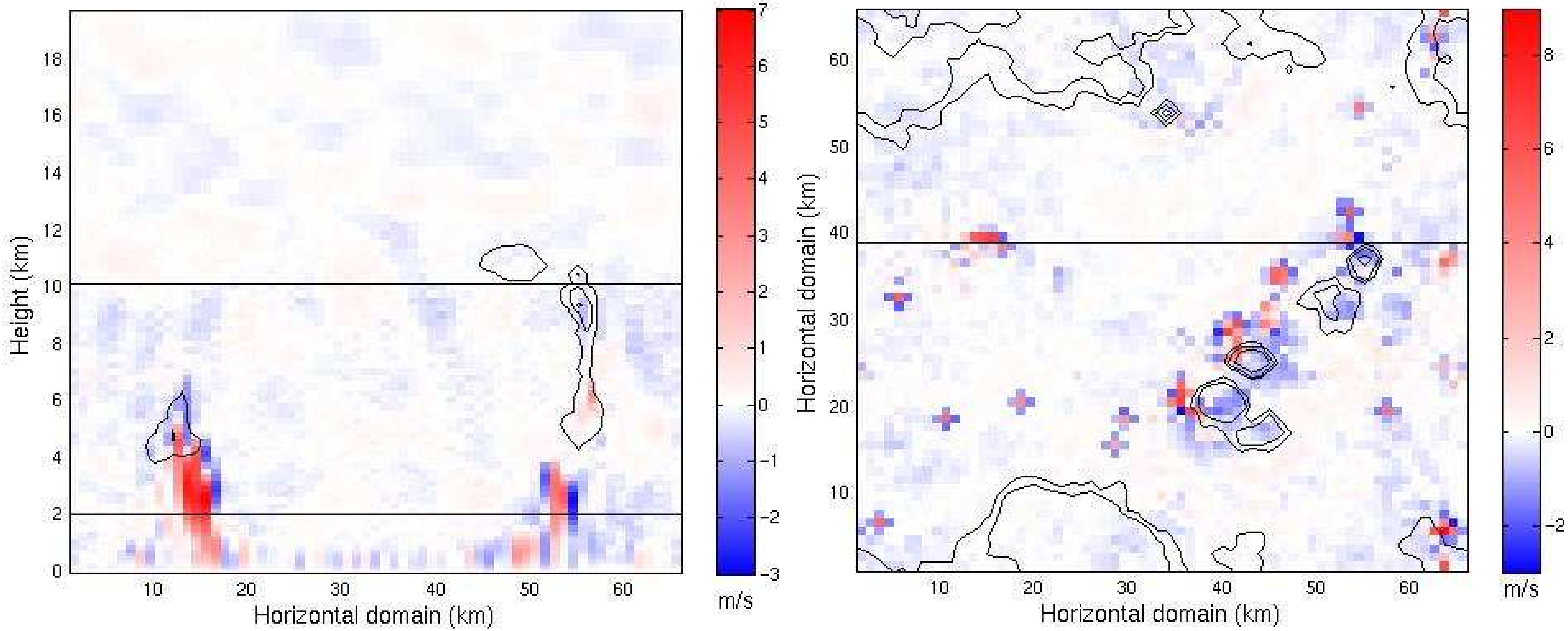
- Now, the system has a finite forcing.
- The total amount of convection is proportional to the amount of forcing.
- Avoids issues of timing and cloud-scale fluctuations.



Forcing method

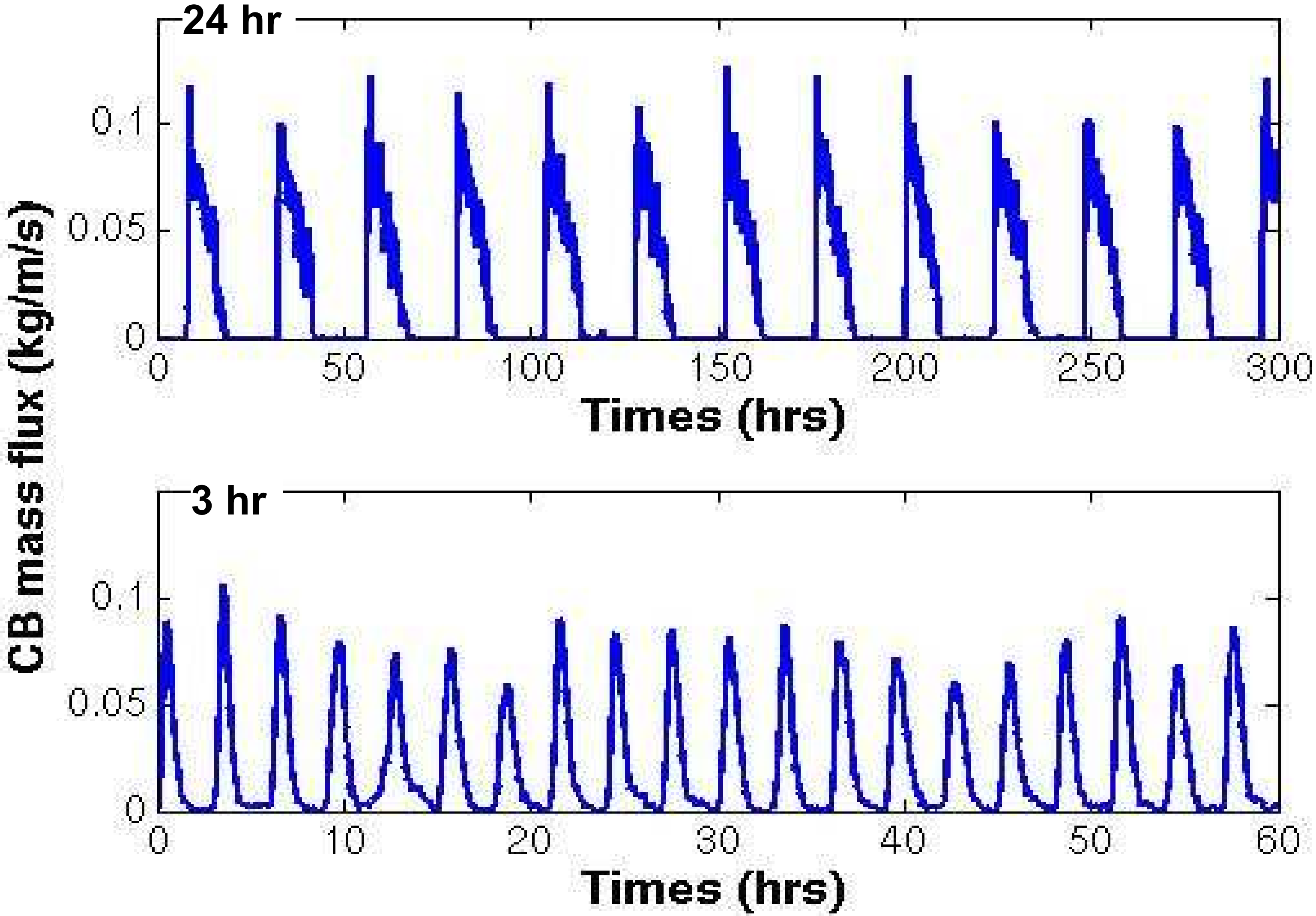


Convective characteristics

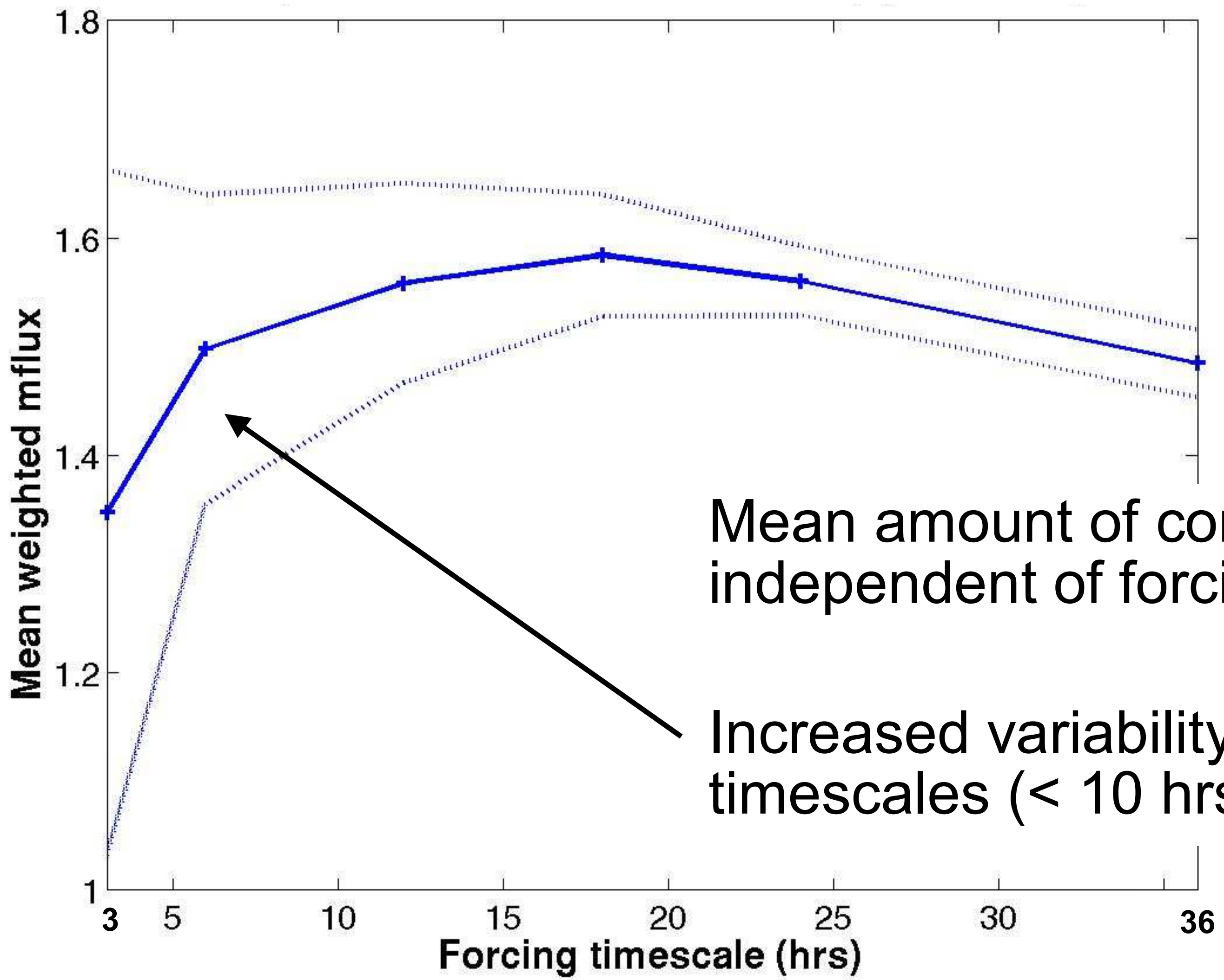


Ice contours 1, 2, 4 x10^{-4} kg/kg

Time evolution



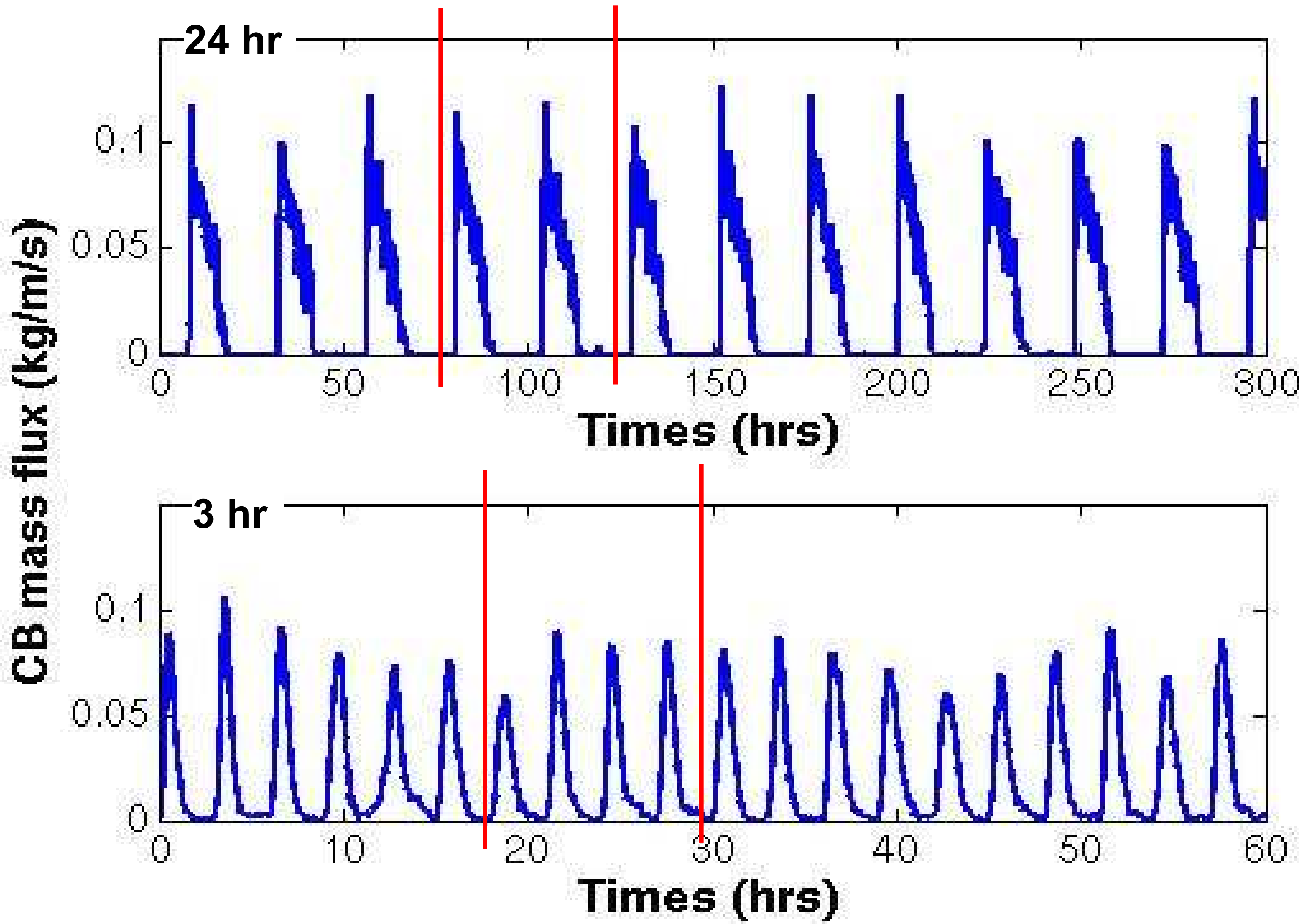
Effect of forcing timescale



Mean amount of convection is almost independent of forcing timescale.

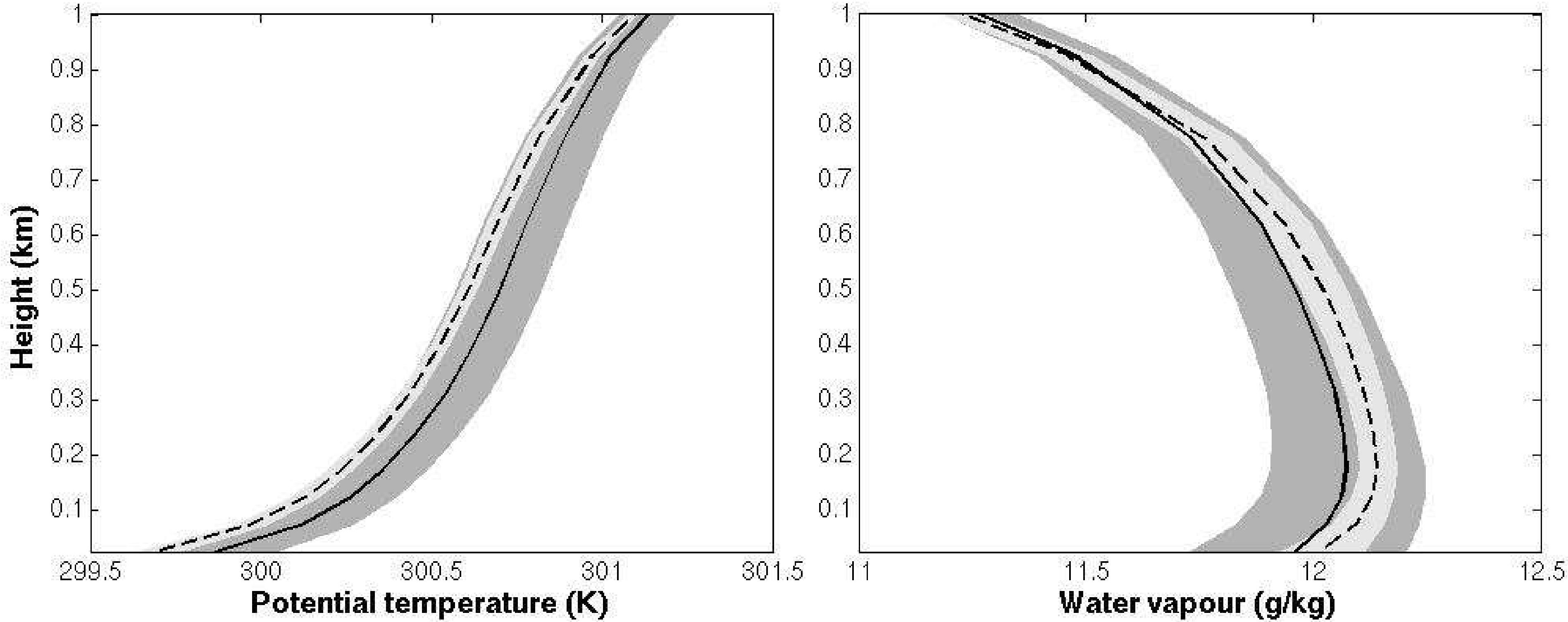
Increased variability at short forcing timescales (< 10 hrs).

Time evolution



Cause of variability

Differences in the mean profiles of θ and q_v?



Mean of initial profiles when total integrated convection exceeds mean ± σ shaded

Mean of initial profiles when total integrated convection is less than mean ± σ shaded

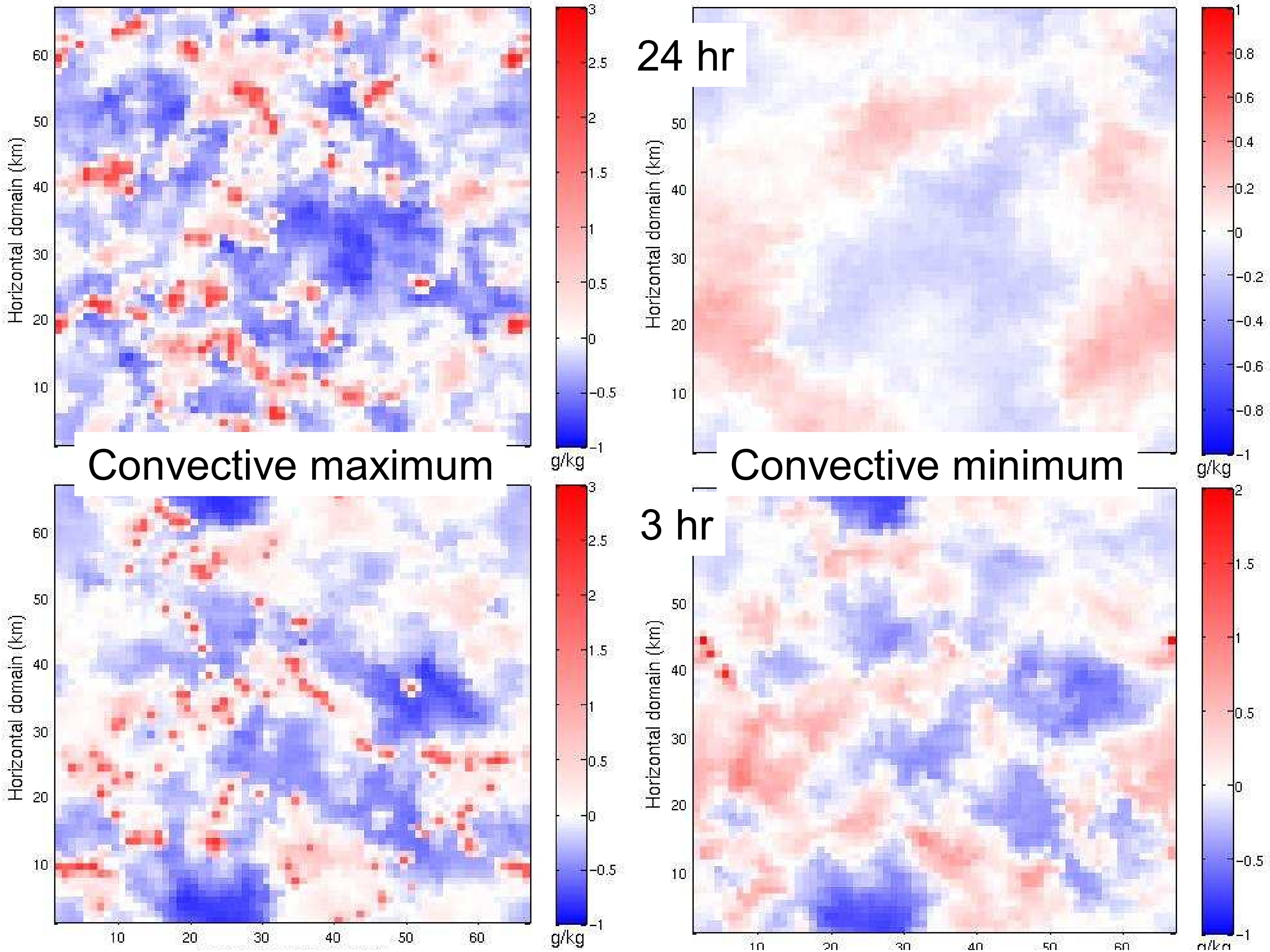
Cause of variability

Differences in the mean profiles of θ and q_v?

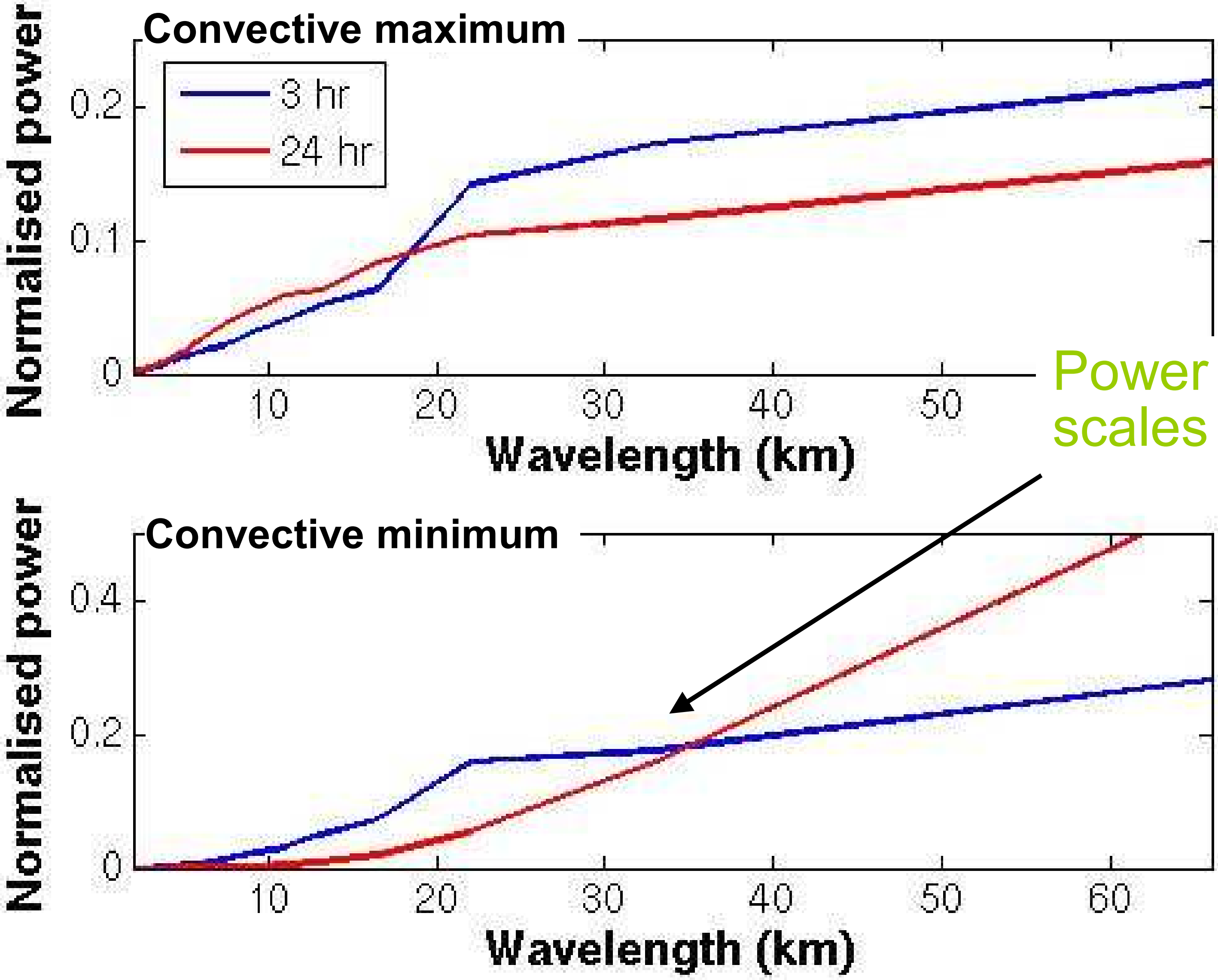
Variability is not explained by initial profiles of θ and q_v in the convective ensemble.

Differences in the spatial variability?

Are there different spatial scales of θ and q_v present initially at different forcing timescales?


24 hr
3 hr
Convective maximum
Convective minimum
Horizontal domain (km)
g/kg

Spatial scales of relative humidity



Power persists at scales 10-30 km.

Conclusions (1)

- LEM simulations confirm that forcing timescale effects the characteristics of the convection

- On forcing timescales < 10 hrs memory effects are observed.

- Memory is carried by spatial structures in moisture field.

Conclusions (2)

- At certain forcing timescales convective systems exhibit signs of memory.

- Inclusion of memory in a parameterisation may improve the representation of convection.

- It is anticipated that at diurnal timescales there may be memory effects.

- Timescales < 10 hrs imply a horizontal spatial scale in the order of 50 km which may be significant for NWP.