Statistical Mechanics and Stochastic Convective Parameterisation

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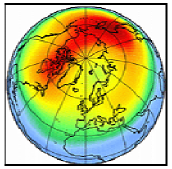
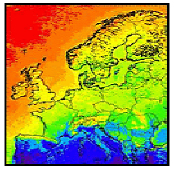
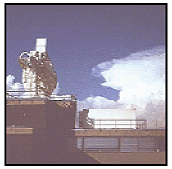
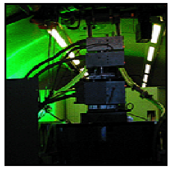
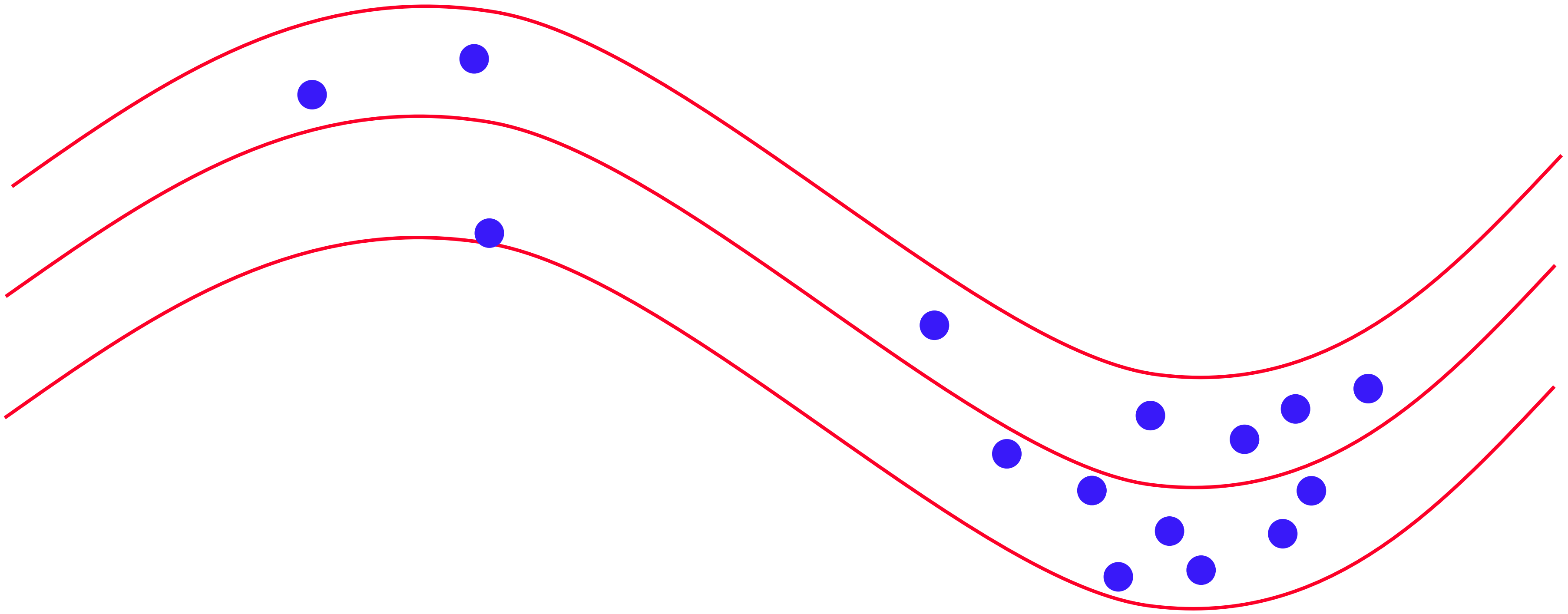


Convective Equilibrium

Convective equilibrium requires scale separation:

- Large scale uniform over region containing many clouds
- Large scale slowly varying so convection has time to respond



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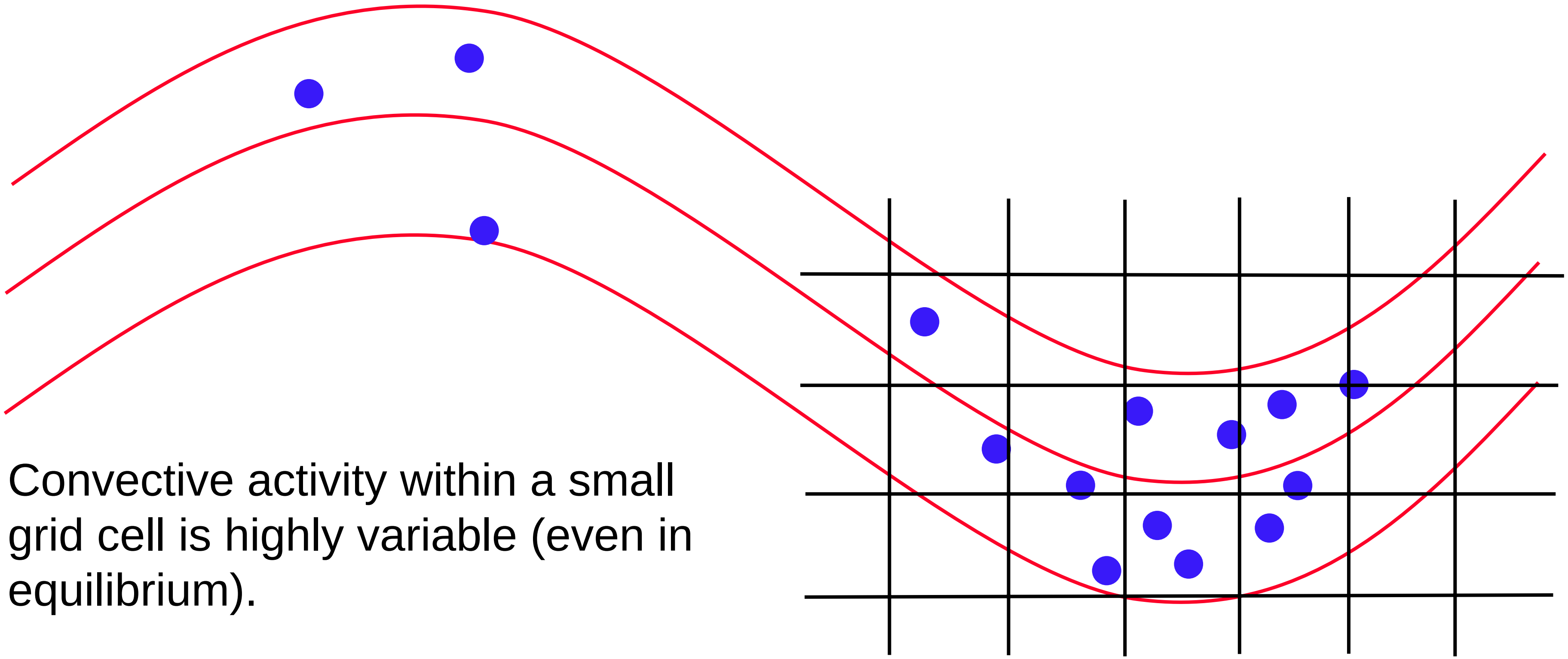


Convective activity within a small grid cell is highly variable (even in equilibrium).

Statistics of convective equilibrium

Parameterisations of cumulus convection are usually based on equilibrium (large scale interacts deterministically with statistical properties of convection)

This is a statistical equilibrium like turbulence or gas kinetics

To understand the limits of equilibrium, need to know underlying processes at the “microscopic” level - individual up- and down-draughts

Questions:

1. Time scale of adjustment
2. Length scale of averaging
3. Magnitude of fluctuations
4. Non-equilibrium dynamics

Aim is to develop a statistical characterisation of convective scale behaviour, given the large scale environment (and test it)

Simulations with a ‘cloud resolving’ model

Simulate an equilibrium field of convective clouds and look at departures from mean behaviour

Resolution:	2 km x 2 km x 50 levels
Domain:	128 x 128 km (256 x 256 km for some experiments)
Boundary conditions:	doubly periodic, fixed SST of 300 K
Forcings:	fixed tropospheric cooling of 2, 4, 8, 12, 16 K day^{-1} vertical wind shear of 0, 0.2 m s^{-1} km^{-1}, 2 m s^{-1} km^{-1}

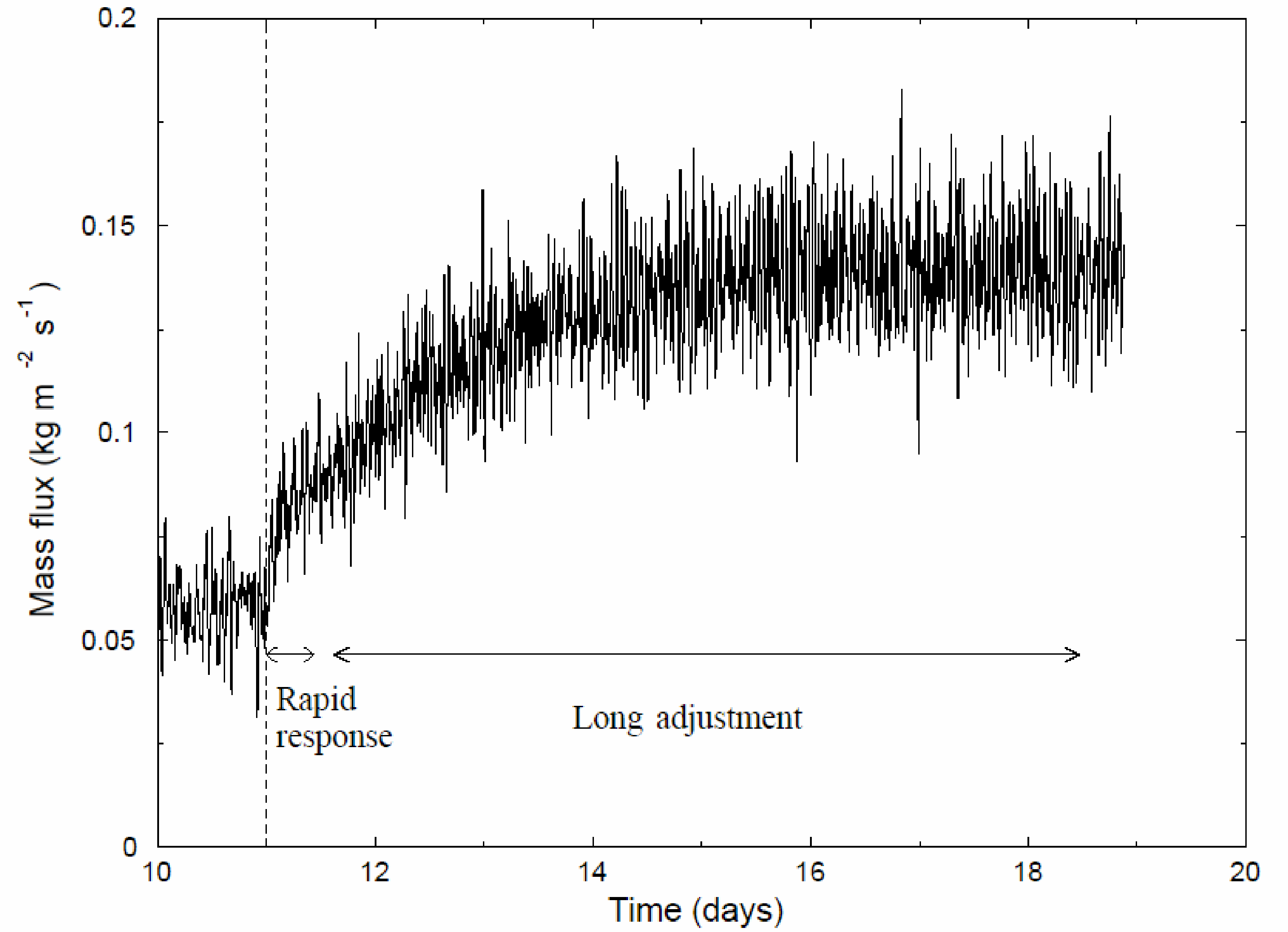
Timescales of Adjustment to a New Equilibrium

Step function perturbation in cooling rate

Convective mass flux adjusts in two stages

1. Rapid (basis for parameterisation)

2. Slow (adjustment of tropospheric moisture)



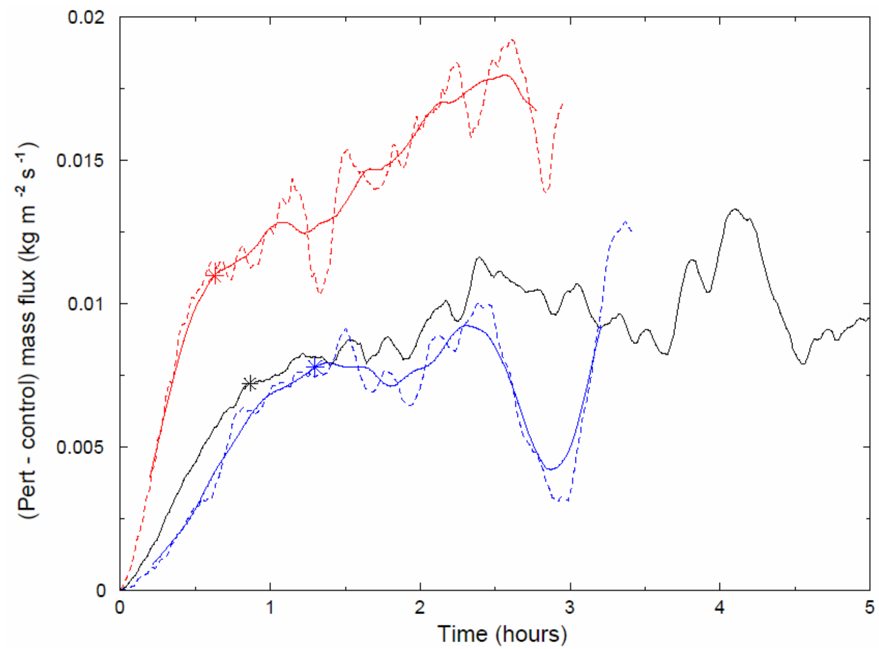
Time scale proportional to cloud spacing

From equilibrium state at -8 K/day forcing, change forcing to -4, -12, -16 K/day.

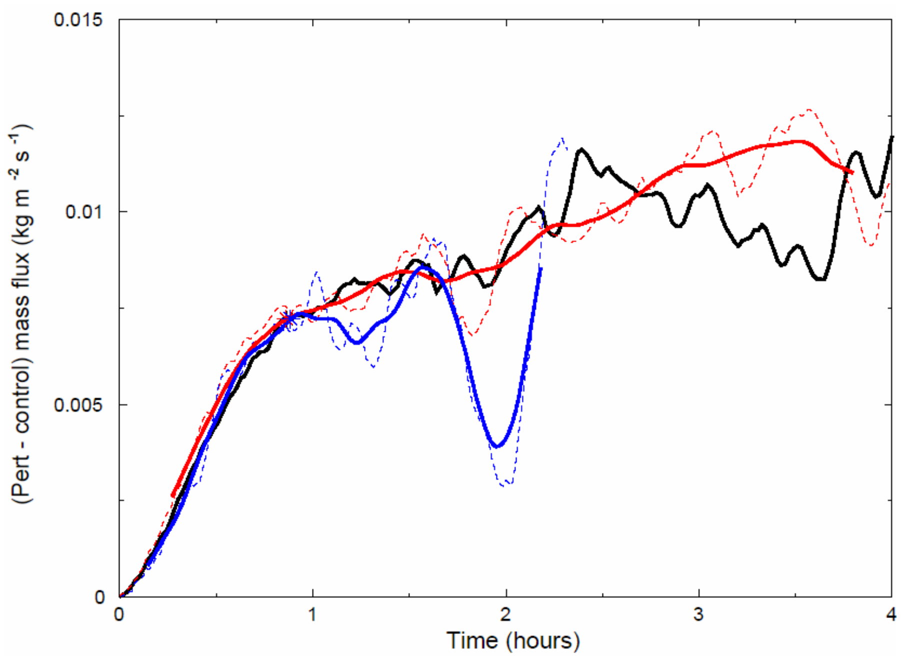
Rescale mass flux time series by quasi-equilibrium value (after rapid adjustment) and time axis by cloud spacing distance.

Perturbation mass flux

Unscaled



Rescaled by cloud spacing



Time (hours)

Mechanism determining adjustment time scale

Time scale is proportional to cloud spacing.

This is consistent with the idea that it is determined by the time required for a gravity wave to cross between the clouds - the time for temperature perturbations to be communicated from convective cores to the rest of the troposphere.

Need experiments with different gravity wave speeds, but we were unable to change this(!)

Note: Cloud number density depends on forcing, so time scale depends on forcing.

Fluctuations in equilibrium

For convection in equilibrium with a given forcing, the mean mass flux should be well-defined.

At a particular time, this mean value would only be measured in an infinite domain.

For a region of finite size,

- What is the magnitude and distribution of the variability?
- What scale must one average over to reduce it to a desired level?

A theory for convective statistics (Gibbs canonical ensemble)

Assume:

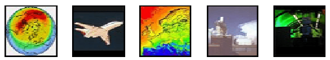
1. Large-scale constraints - mean mass flux within a region: $\langle M \rangle$
   mean mass flux per cloud: $\langle m \rangle$

2. Scale separation - environment sufficiently uniform in time and space to average over a large number of clouds

3. Weak interactions - clouds feel only mean effects of total cloud field (no organisation)

4. Equal *a priori* probabilities - all locations and mass fluxes for a cloud are equally probable

Choose the most probable distribution subject to these constraints



Predicted Distributions

The frequency of clouds with a given mass flux follows a Boltzman distribution:

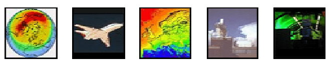
$$d\bar{n}(m) = \frac{\langle N \rangle}{\langle m \rangle} e^{-m/<m>} dm \qquad (1)$$

The total mass flux within a region is given by:

$$p(M) = \left(\frac{\langle N \rangle}{\langle m \rangle} \right)^{1/2} e^{-\langle N \rangle} M^{-1/2} e^{-M/\langle m \rangle} I_1 \left(2 \left(\frac{\langle N \rangle}{\langle m \rangle} M \right)^{1/2} \right) \qquad (2)$$

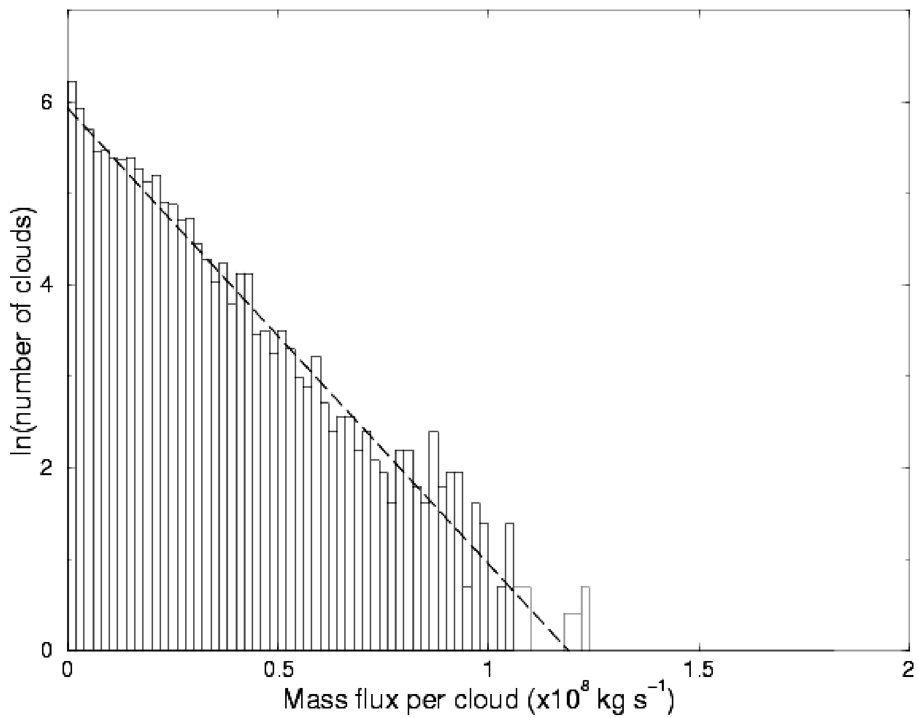
which has variance:

$$\frac{\left\langle (\delta M)^2 \right\rangle}{\langle M \rangle^2} = \frac{2}{\langle N \rangle} \qquad (2a)$$

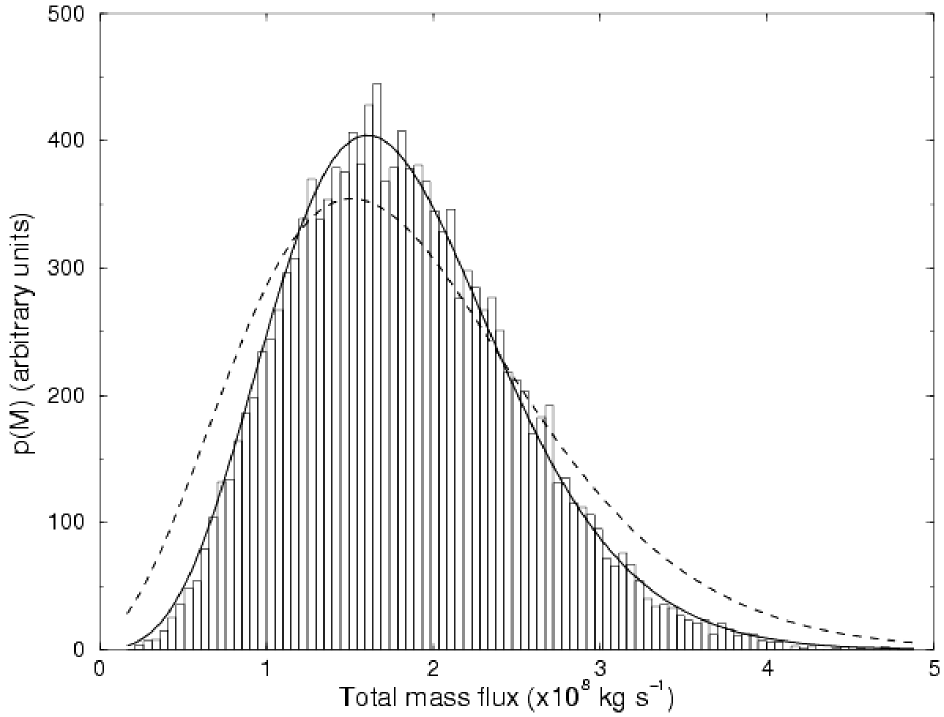


CRM distributions of cloud mass flux

Mass flux per cloud



Total mass flux in domain



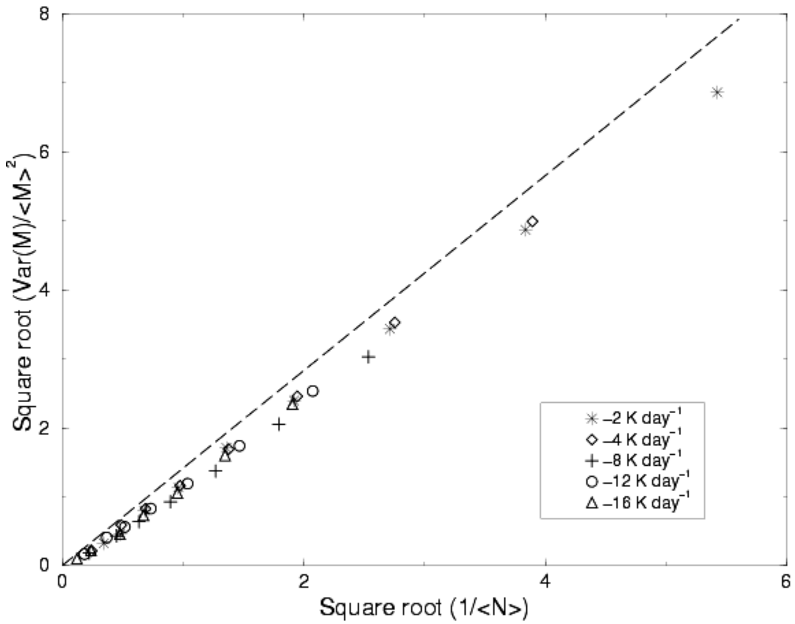
2 K/day, no shear

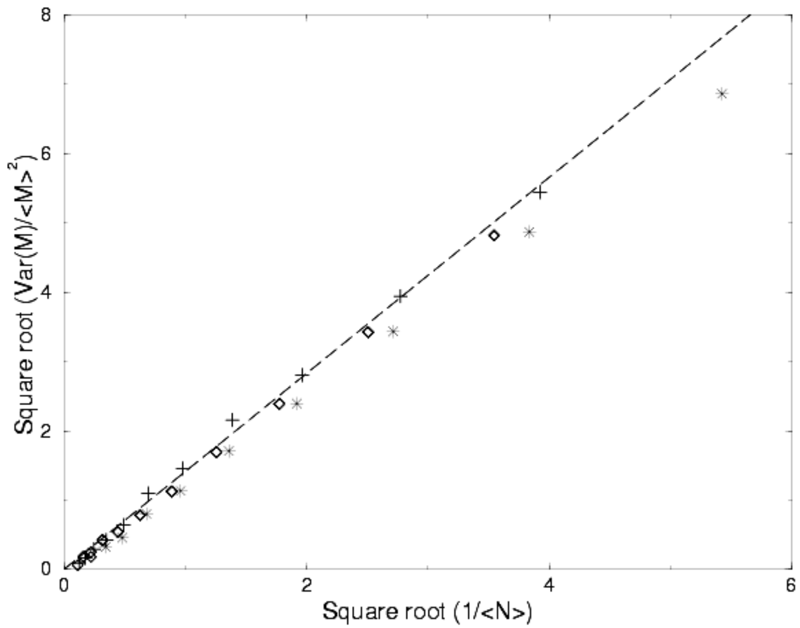
CRM mass flux variance as function of region size

Cooling Rate (cloud spacing)

Shear (organisation)

Normalised std. dev.

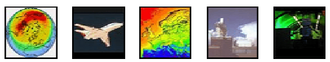




(cloud spacing)/(region size)

large region

small region



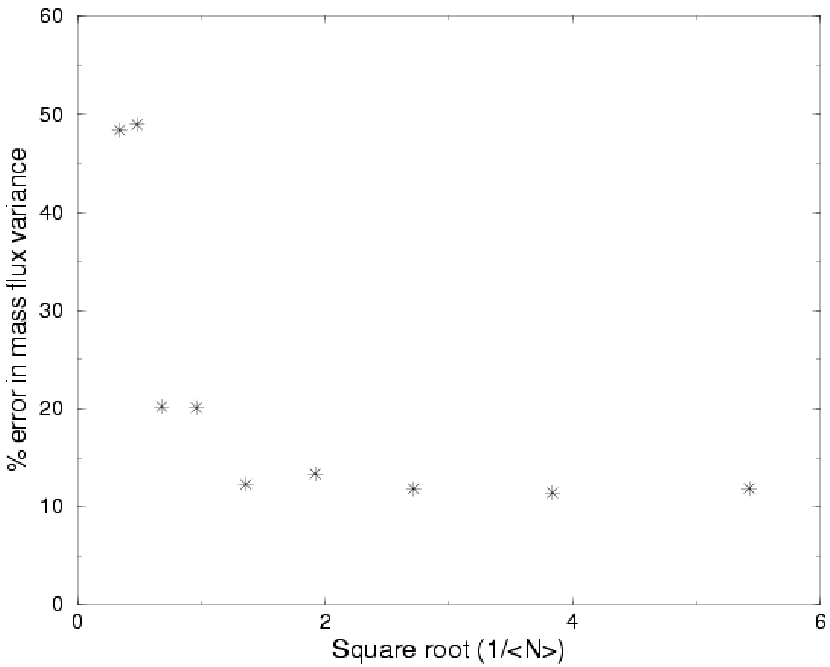
Finite Domain Effects

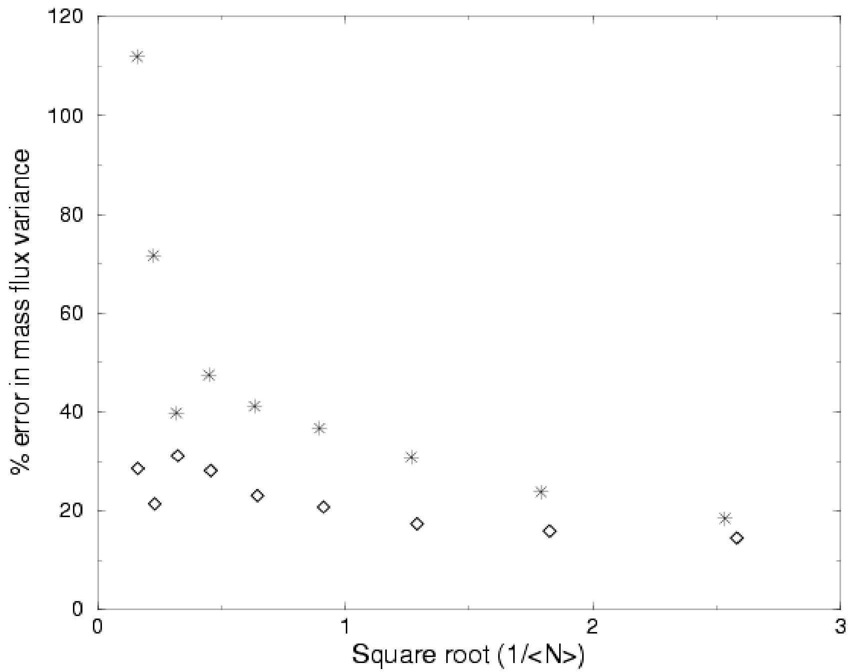
Finite sized domain can impose unphysical regularity, leading to reduced variance

Reduction largest for
averages over whole domain

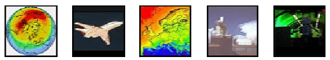
Reduction reduced if
domain size increased

% reduction in std. dev.





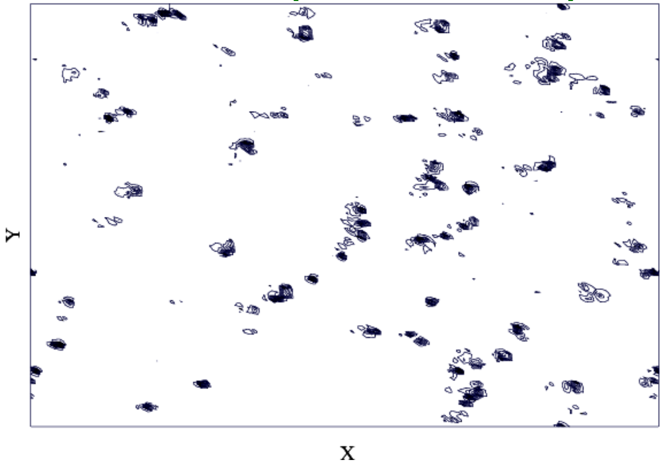
(cloud spacing)/(region size)



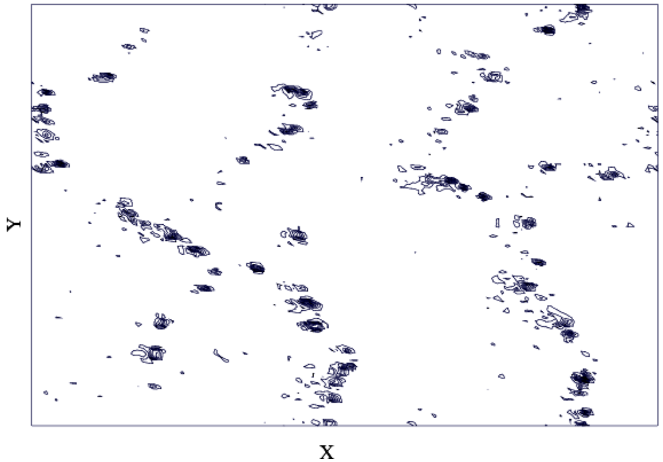
Effects of organisation

w at z = 2.8 km

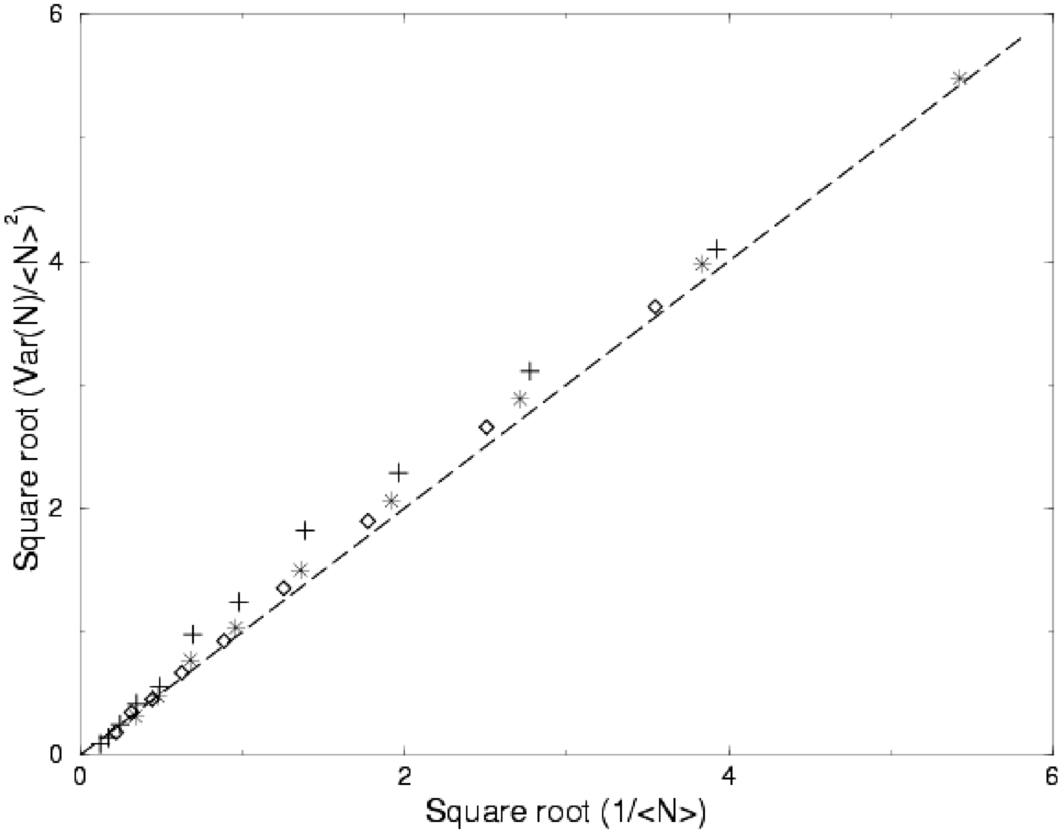
Weak shear (0.2 m/s/km)



Strong shear (2 m/s/km)



Cloud number variance



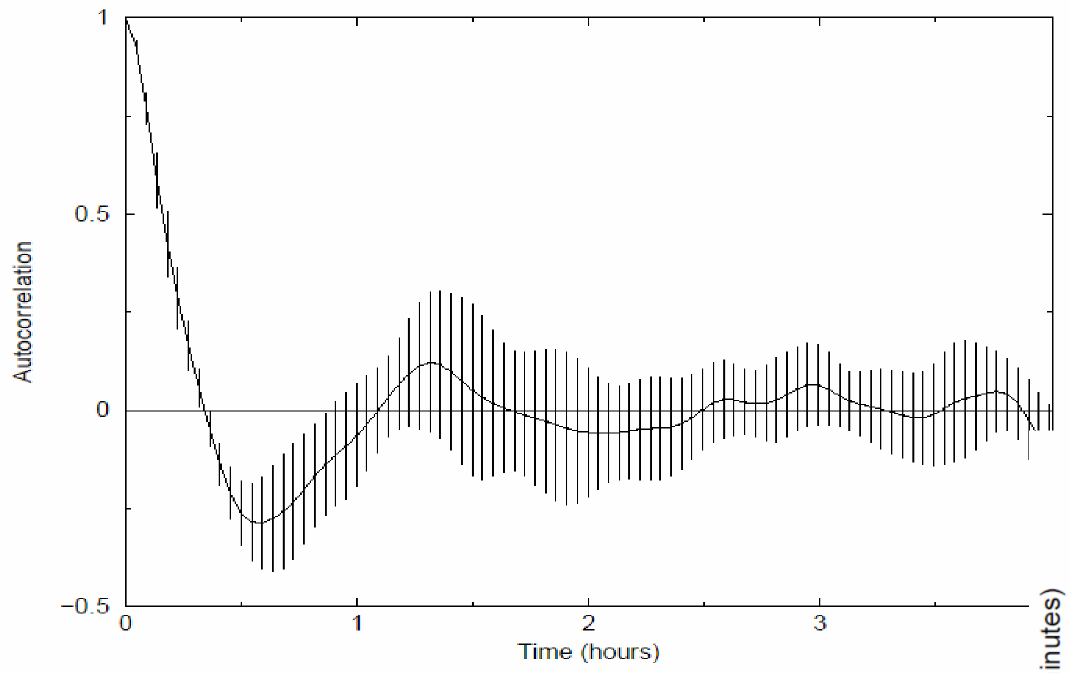
Fluctuation-Dissipation Theorem

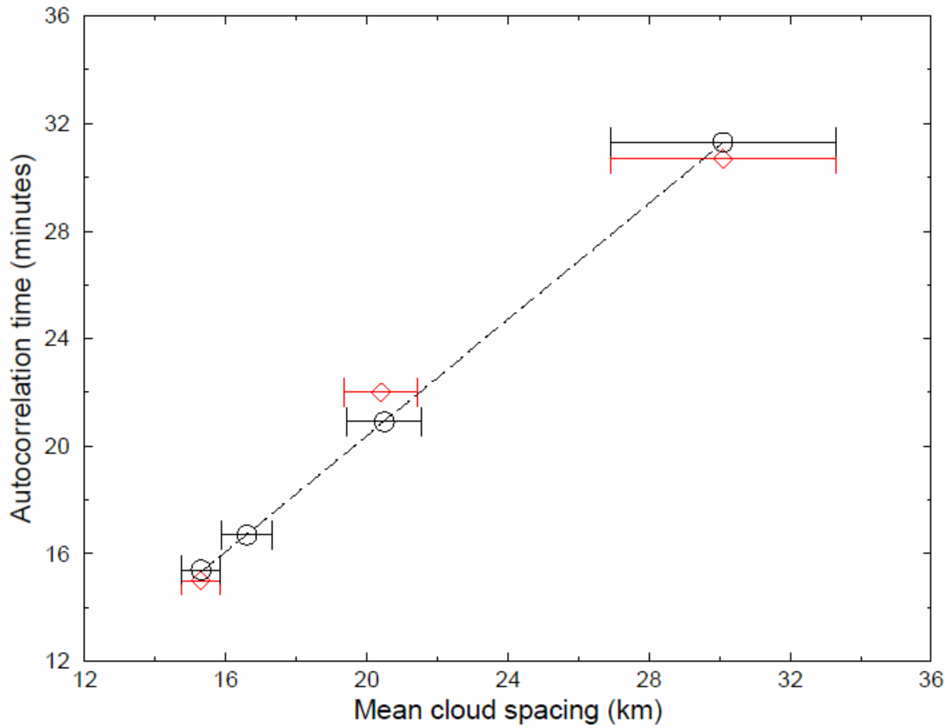
For systems close to equilibrium (linear-response regime), the response to a change in external forcing is the same as autocorrelation of fluctuations in the equilibrium state

The return to equilibrium after an external forcing perturbation is released is indistinguishable from the relaxation after a spontaneous fluctuation.

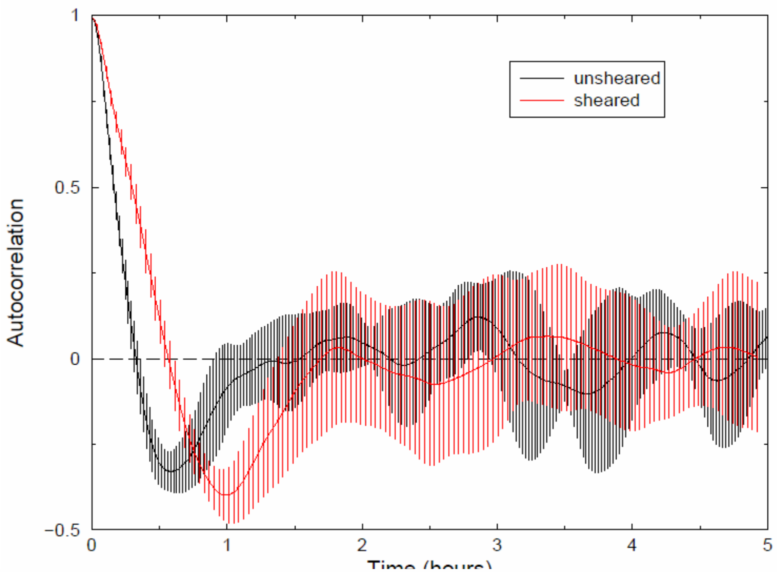
$$\frac{\langle M(t)\rangle - \langle M(0)\rangle}{\langle M\rangle} = \frac{\langle M(t)M(0)\rangle}{\langle M\rangle^2}$$

Autocorrelation of Mass Flux





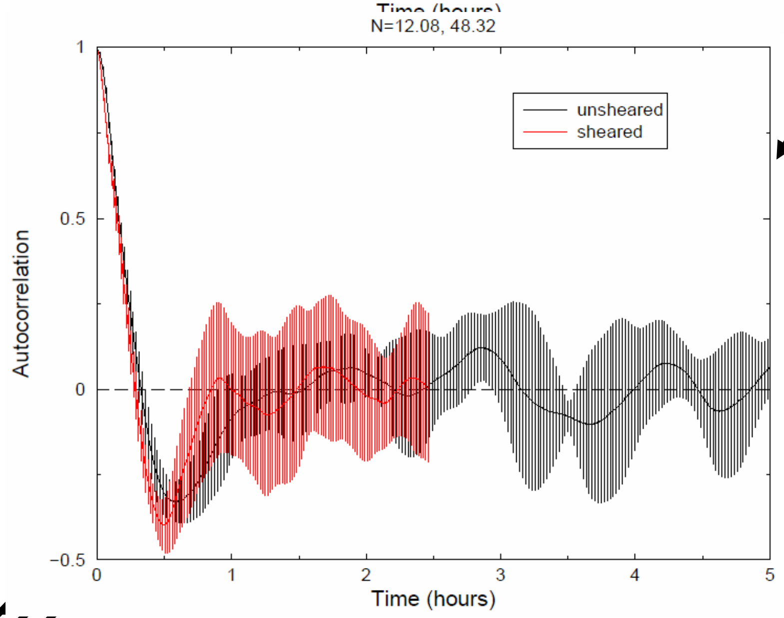
Mass Flux Autocorrelation (strong shear)

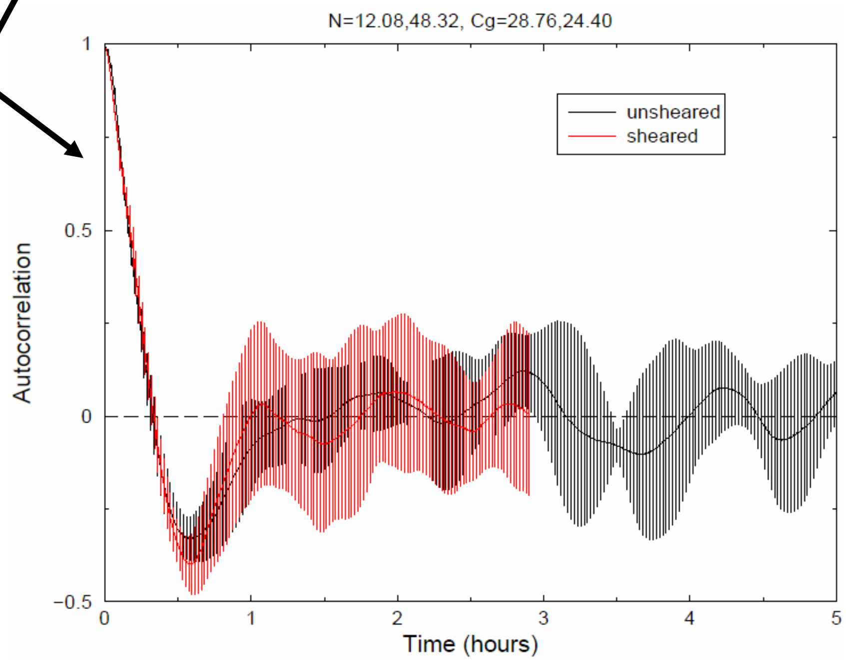


Unscaled

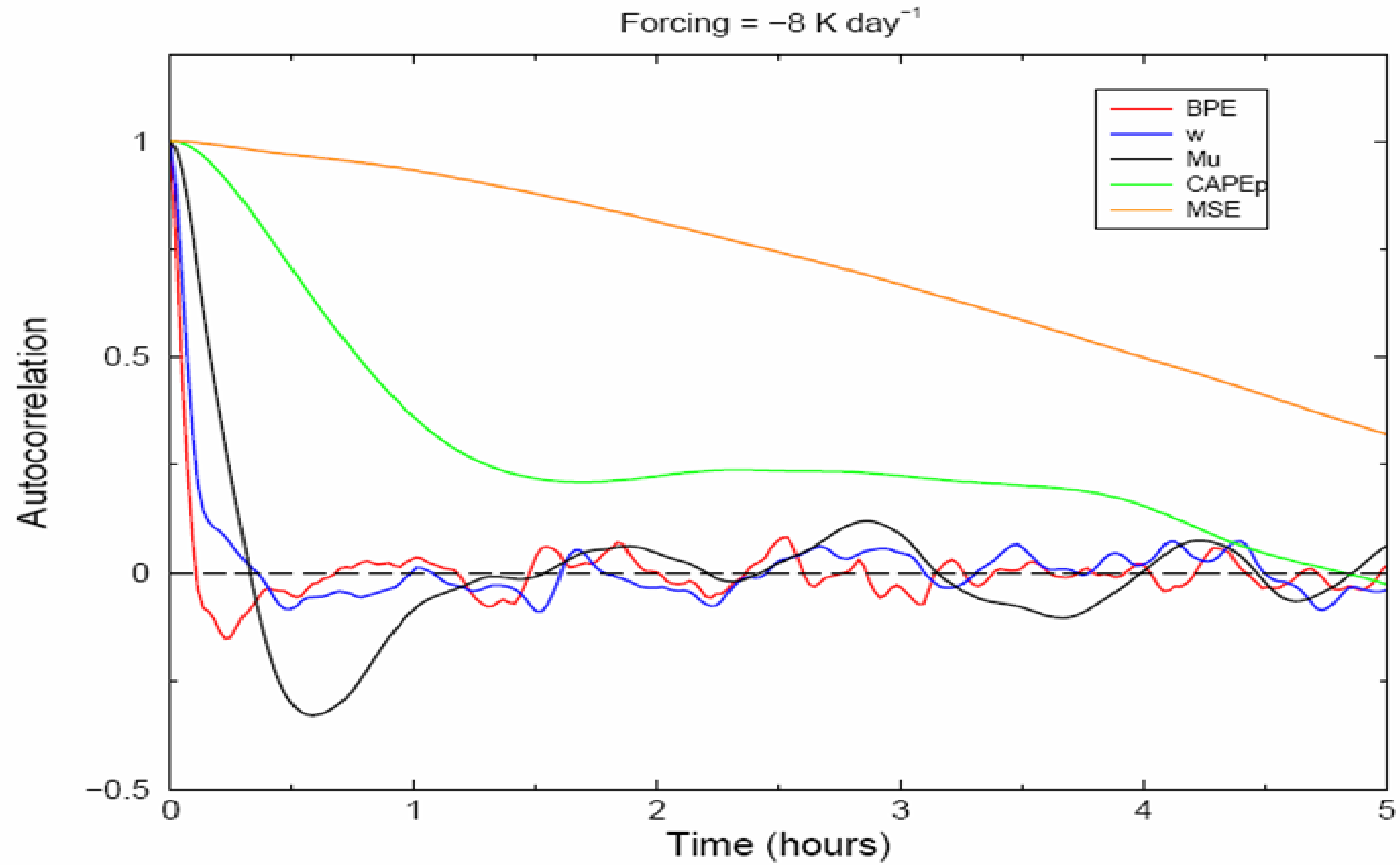
Rescaled by cloud spacing

Rescaled by cloud spacing and mean gravity wave speed





Autocorrelation Functions



Outline of a Stochastic Cumulus Parameterization Scheme

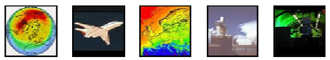
Designed to give the correct variability where the correct variability is known

Mass flux formalism (based on Kain-Fritsch)

1. no trigger function- presence/absence of convection in equilibrium is due to random subgrid variability

2. Cloud model - ensemble of plumes with exponential distribution of cloud base mass flux m; each plume acts as representative cloud of given m

3. CAPE Closure - CAPE determined from mean sounding (convective variability averaged out); total mass flux scaled to remove CAPE over timescale proportional to forcing



Single Column Model Tests

Met Office Unified Model - single column version

- parameterizations for boundary layer transport, stratiform cloud
- forced as in CRM experiment (fixed tropospheric cooling)
- 20 min timestep
- CAPE closure based on sounding averaged over 100 timesteps

Questions:

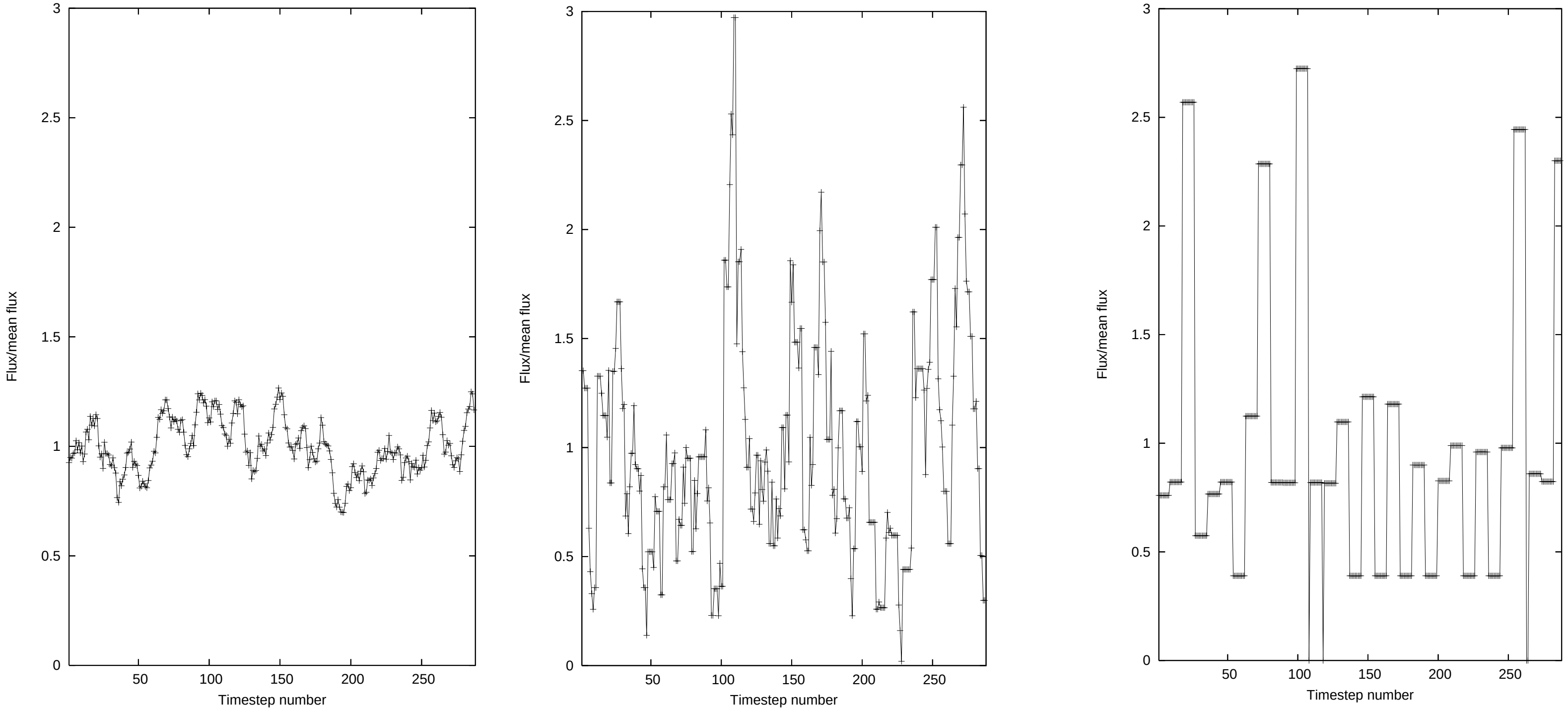
0. Does a steady forcing give a steady response (in the limit of a large grid box)?
1. Are the mean state temperature and humidity profiles sensible (not worse than Kain-Fritsch)?
2. Are the properties of the individual plumes sensible (*m* constant with height, exponential distribution)?
3. Is the desired distribution of *M* obtained for finite-sized grid boxes (can the convective variability be averaged away)?

Variability of Convective Mass Flux in SCM

Stochastic Scheme

(400 km)^2 | (64 km)^2 | Kain-Fritsch

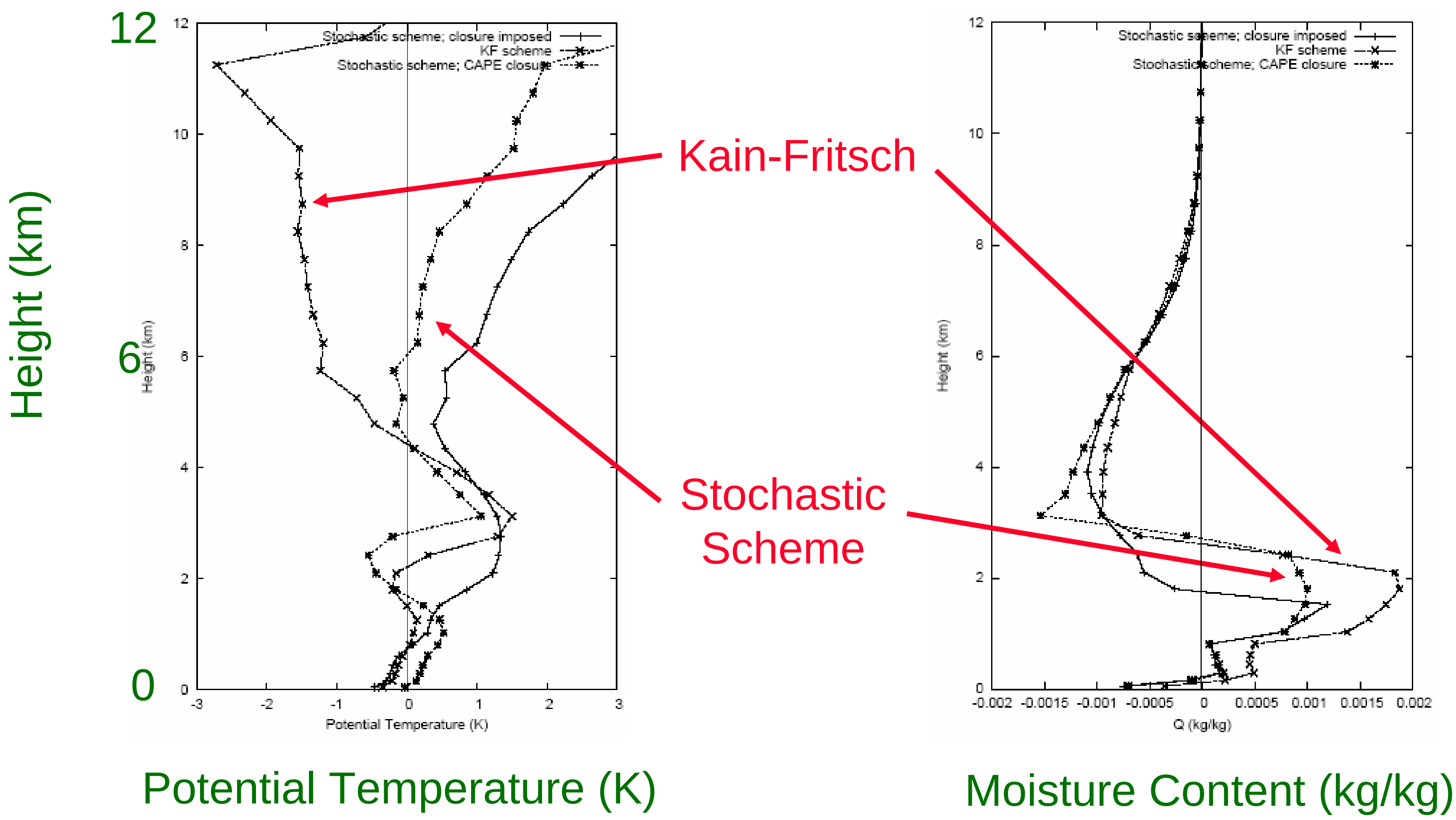
Normalized Mass Flux



0 100

Time (hrs)

Single Column Equilibrium - Deviation of mean from CRM



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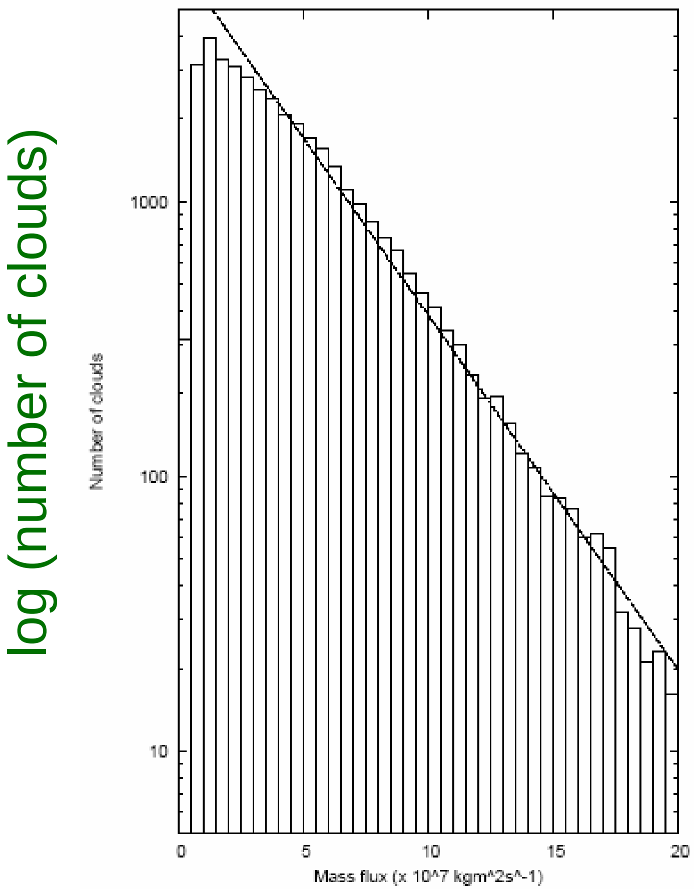
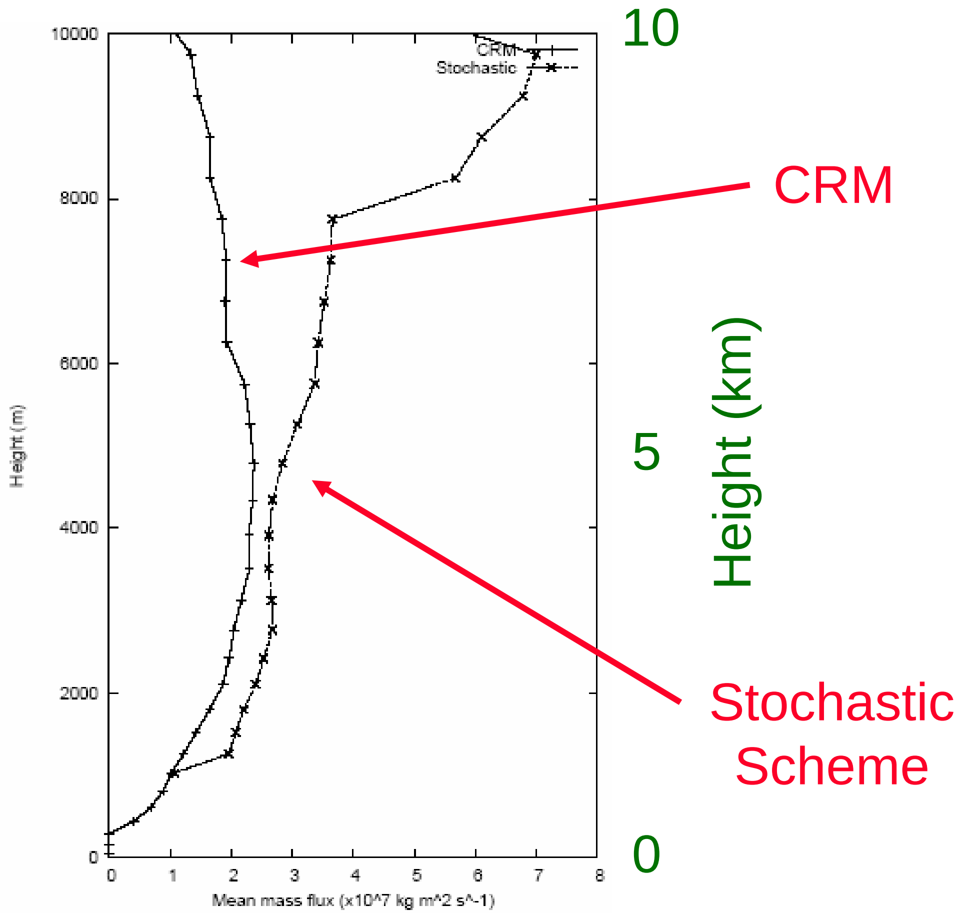
Cloud Mass Flux Distribution in SCM Equilibrium

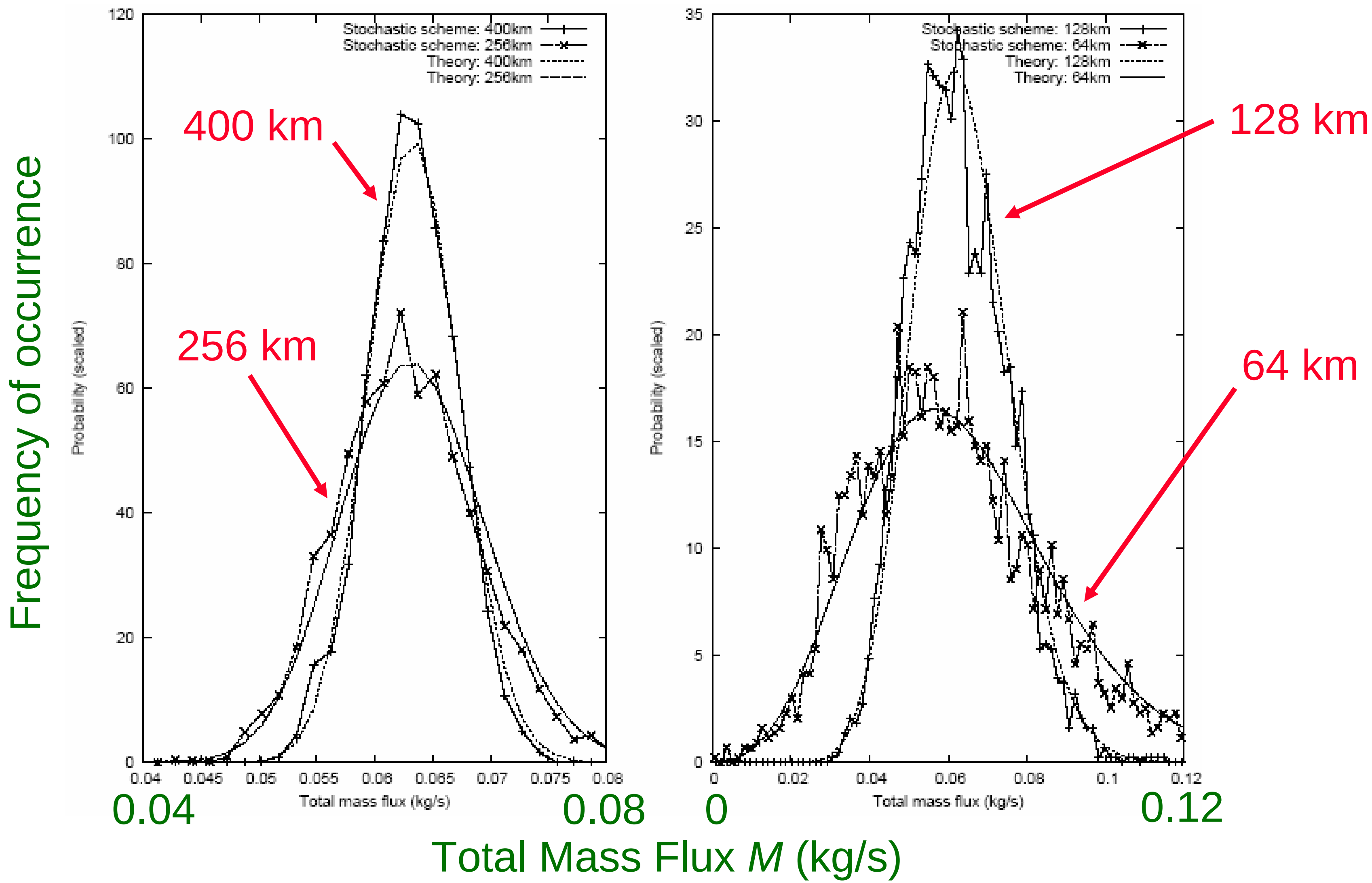


Cloud mass flux
at z = 5.75 km



Mean cloud mass flux

Distribution of Total Cloud Mass Flux *M*



Status and Outlook for Stochastic Parameterisation

In Progress

- SCM tests completed
- implementation in full Met Office Unified Model in progress (not trivial since non-local)

Planned

- radiative-convective equilibrium tests in mesoscale UM
- implementation in DWD Lokal Modell (regional NWP model)
- testing in COSMO-LEPS ensemble forecasting system

Possible (if someone wants to do it)

- longer term trial in COSMO-LEPS
- Aquaplanet global UM
- general availability

Summary

- Time scale of adjustment to equilibrium proportional to cloud spacing (gravity wave?)

- Gibbs canonical ensemble leads to expressions for fluctuation properties

- CRM confirms predictions (to within ~10%), with influence of organisation found to be weak

- Fluctuation-dissipation theorem may allow autocorrelation to be used to probe non-equilibrium dynamics (in the linear-response regime)

- Fluctuation expressions serve as basis for a stochastic cumulus parameterisation (working in single column tests)