Stochastic Representation of Convection

RMS Dynamical Problems Group
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Outline

1. The need for a stochastic representation of convection
2. Some experiments so far
3. A stochastic scheme
4. Tests of scheme
5. Outlook

Why a stochastic representation?

A much harder question is...

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What makes you think you can get away with using a deterministic representation?

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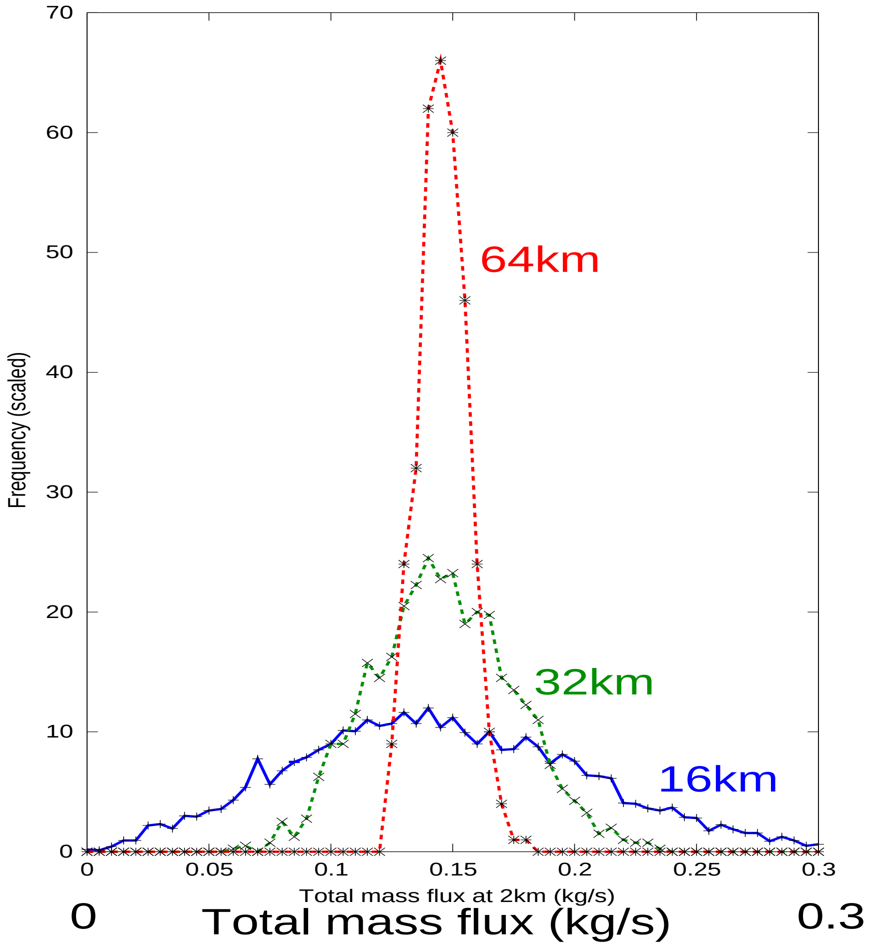
Fluctuating component of sub-grid motions may have important interactions with large-scale

Range of States



Distribution of mass fluxes in CRM simulation of radiative-convective equilibrium over ocean. Uniform SST and forced with constant tropospheric cooling. Averaged over various areas.

Also Xu et al (1992); Shutts and Palmer (2004)

Practical Motivations

Stochastic parameterizations may resolve known problems with current approaches:

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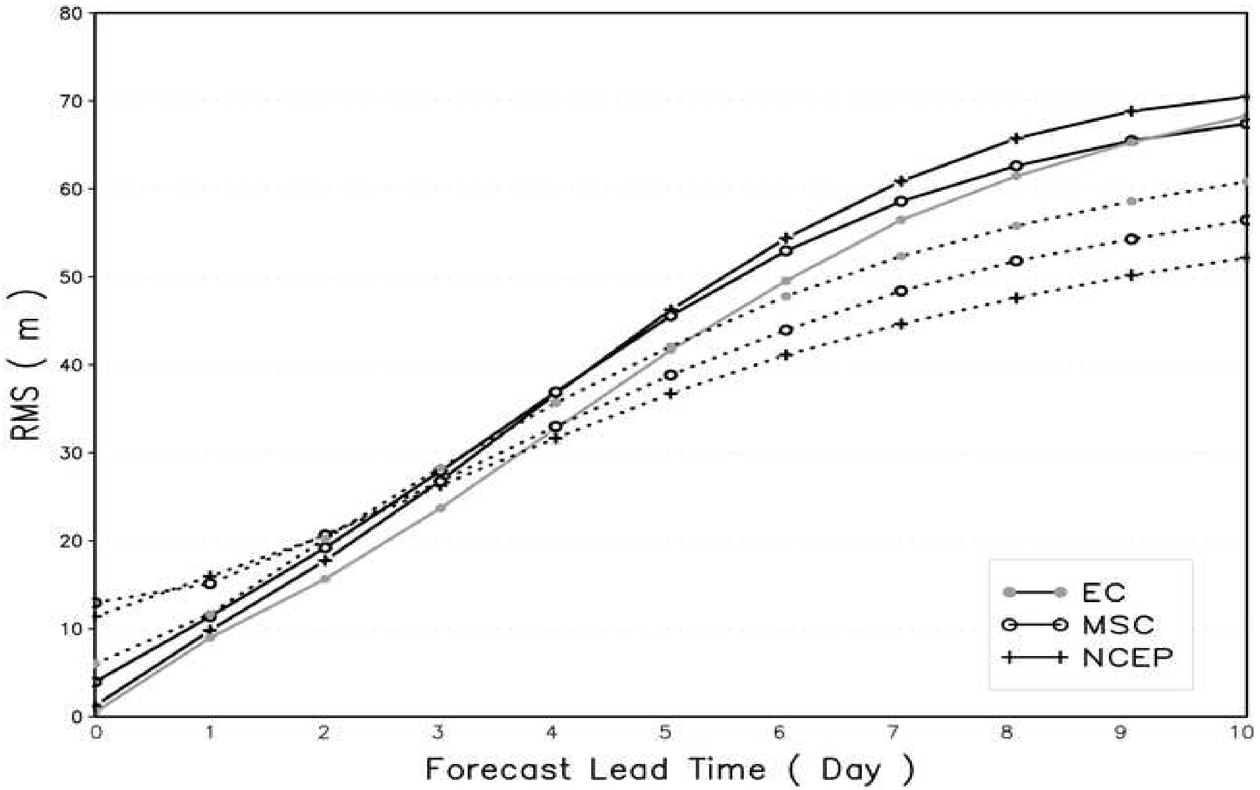


Buizza et al (2005)

Practical Motivations

Stochastic parameterizations may resolve known problems with current approaches:

- NWP models have insufficient ensemble spread (improvement expected)
- Low frequency variability (improvements likely)

  Marginal predictability of some events which react strongly to near-grid-scale noise (Zhang et al 2003)

  GCMs have insuffi cient variability in tropics (impact on QBO)
- Systematic model errors (hopeful of improvements)

  eg, propagation of convection

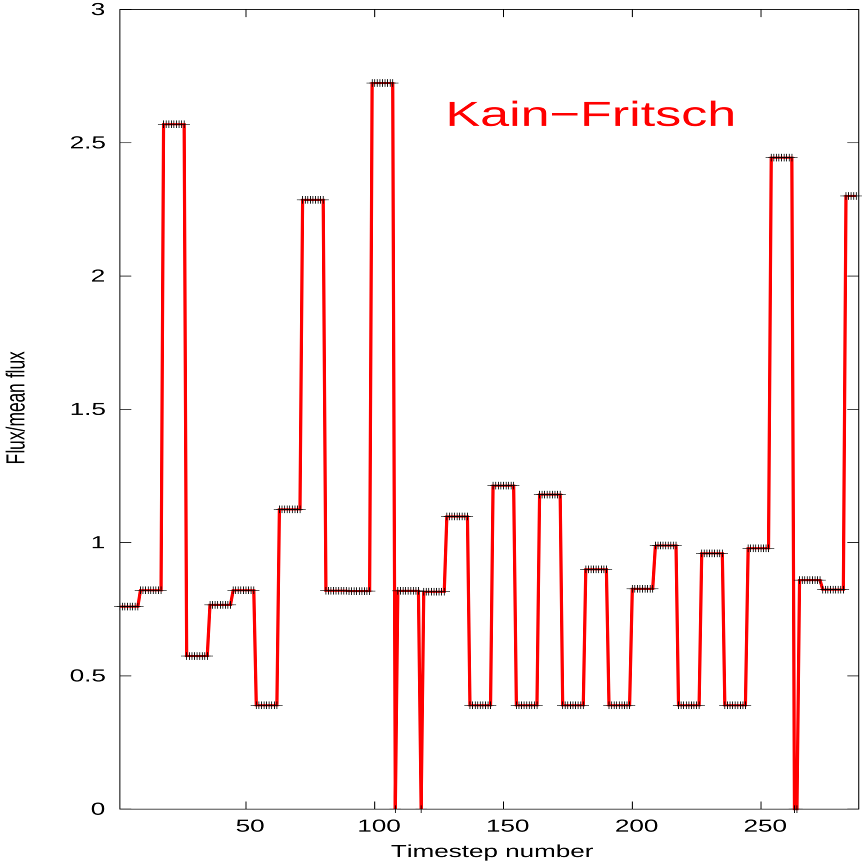
Not a magic wand - some problems will not go away

Existing Variability

Existing parameterizations do have variability, but it is:

- unphysical (numerical)
- uncontrolled
- does not exhibit the correct dependencies

Example of Artificial Variability



Normalized response to a constant forcing by Kain-Fritsch scheme over one day in a SCM

No dependence on (for example) grid size.

Some stochastic experiments

Variability in Model Formulation

- In ECMWF ensemble system, scale parameterization tendencies,

$$\mathrm{Tendency} = \mathrm{D} + (1 + \varepsilon)\mathrm{P}$$

  Improves ensemble spread

- Bright and Mullen (2002): stochastic perturbation to KF trigger.

  Increased skill and dispersion of short-range precipitation forecasts

- Lin and Neelin (2002): add noise to CAPE closure of Zhang/Macfarlane scheme in CCM3.

  Increase variance of daily tropical precipitation

- Khouider, Majda and Katsoulakis (2003). Spin-flip model.

  Sites within each grid box that may or may not support deep convection.

  Convective heating scales with fractional area.

Aim

To construct a stochastic scheme in which

- the character and strength of the noise has a physical basis
- the physical basis is supported (or inspired) by CRM studies
- physical noise $>>$ numerical noise from scheme
- noise $\rightarrow 0$ if there are very many clouds and in this limit scheme behaves no worse than standard deterministic schemes

A Stochastic Scheme

Basic Structure

Mass-flux formalism (based on Kain-Fritsch)...

- No trigger function. Presence of convection dictated by random subgrid variability.
- Spectrum of possible plumes chosen from distribution of mass fluxes. Each plume represents cloud of given mass flux.
- Clouds persist for finite lifetime $\neq$ timestep.
- CAPE closure to remove instability on a timescale that depends on forcing. Calculations performed on an averaged (non-local) sounding.

Statistical Mechanics I

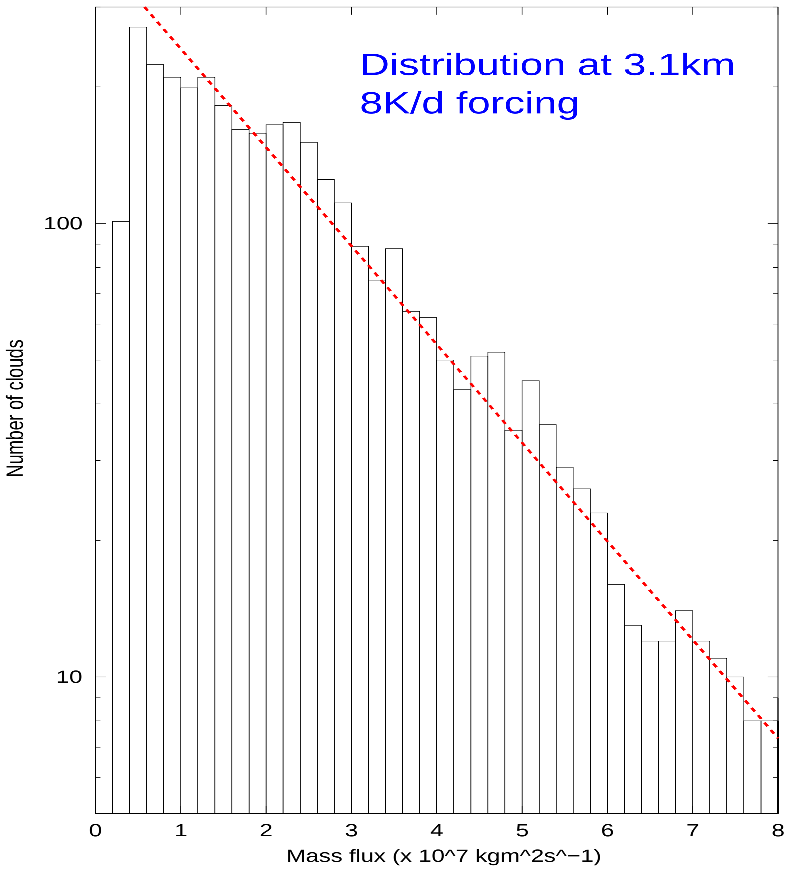
Craig and Cohen (2004)

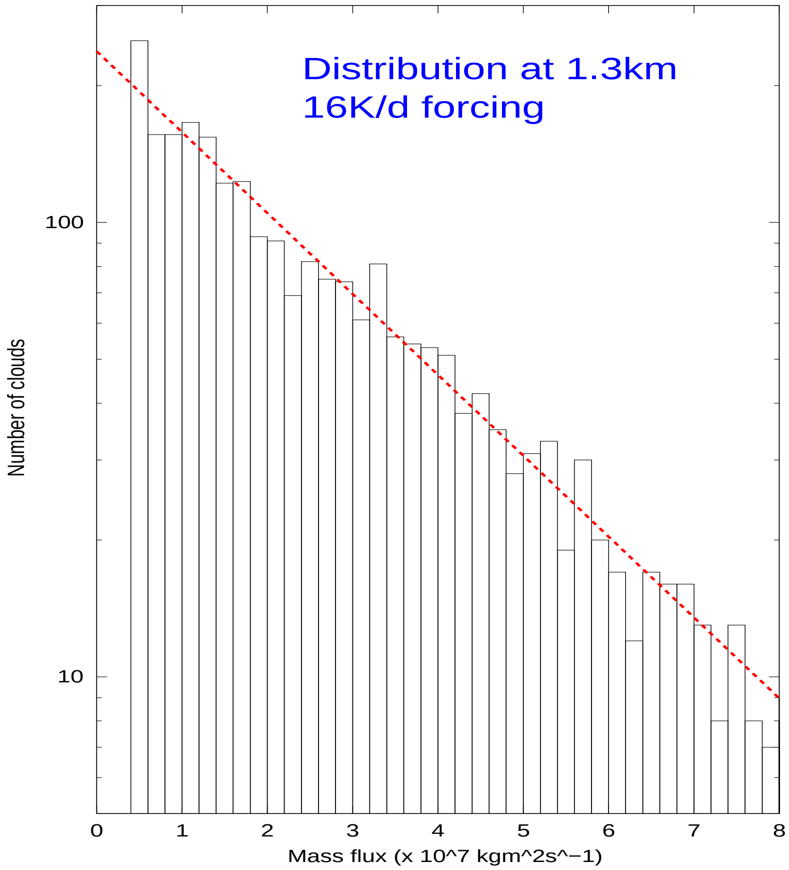
- Weakly-interacting, point-like convective cells in equilibrium with large scale forcing have exponential distribution of mass flux per cloud

$$p(m)dm = \frac{1}{\langle m \rangle} \exp\left(\frac{-m}{\langle m \rangle}\right) dm$$

- cf Boltzmann distribution of energies
- Ensemble mean mass flux $\langle M \rangle$ and is mean mass flux per cloud $\langle m \rangle$ functions of large-scale forcing only

Example Distributions





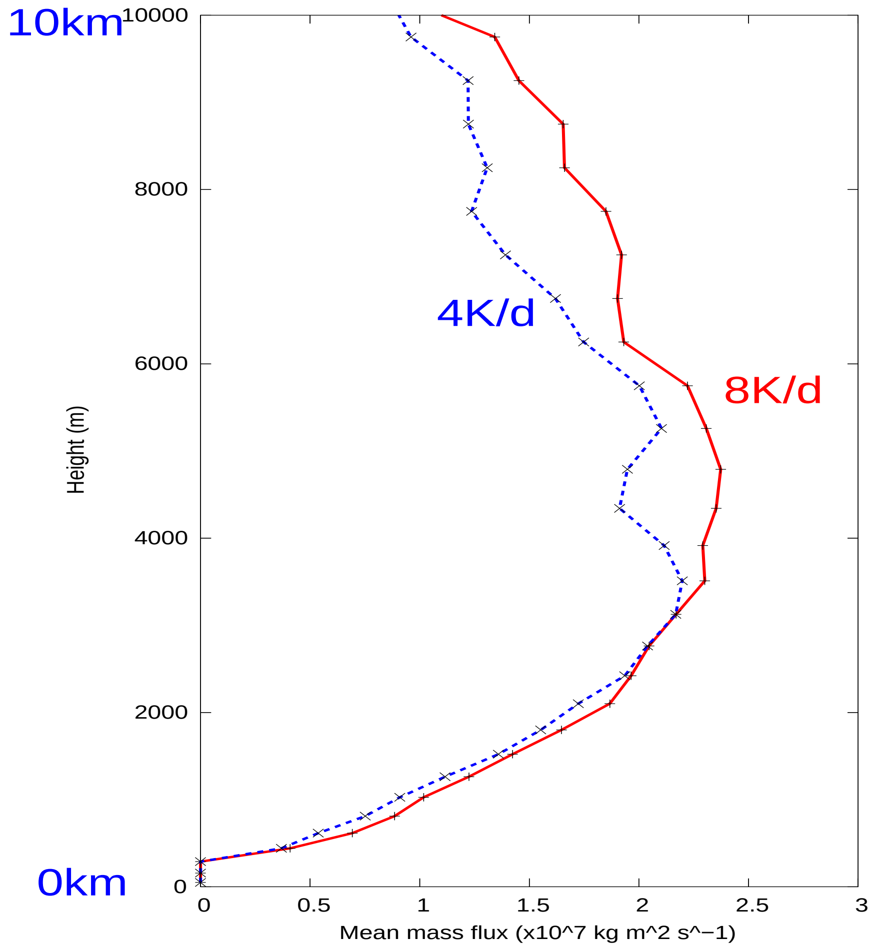
Statistical Mechanics II

- Number of clouds in given region given by Poisson distribution if clouds randomly distributed in space.
- This gives pdf of the total mass flux

$$p(M) = \frac{1}{\langle M \rangle} \sqrt{\frac{\langle M \rangle}{M}} \exp\left(-\frac{M + \langle M \rangle}{\langle m \rangle} \right) I_1 \left(\frac{2}{\langle m \rangle} \sqrt{\langle M \rangle M} \right)$$

- Deviations modest if a wind shear imposed

$\langle m \rangle \sim$ constant at fixed level



Increased forcing predominantly affects cloud number $\langle N \rangle = \langle M \rangle / \langle m \rangle$

- not the mean w (scalings of Emanuel and Bister 1996; Grant and Brown 1999)
- nor the mean size (Robe and Emanuel 1996; Cohen 2001)

Implications for Parameterization

- In each grid box, probability of finding cloud of given m from exponential
- $\langle m \rangle$ taken as constant from CRM data
- Behaviour of each cloud modelled based on 1D Kain-Fritsch plume model
- Exponential distribution imposed at LCL but distribution free to evolve at other levels
- Need closure for $\langle M \rangle$

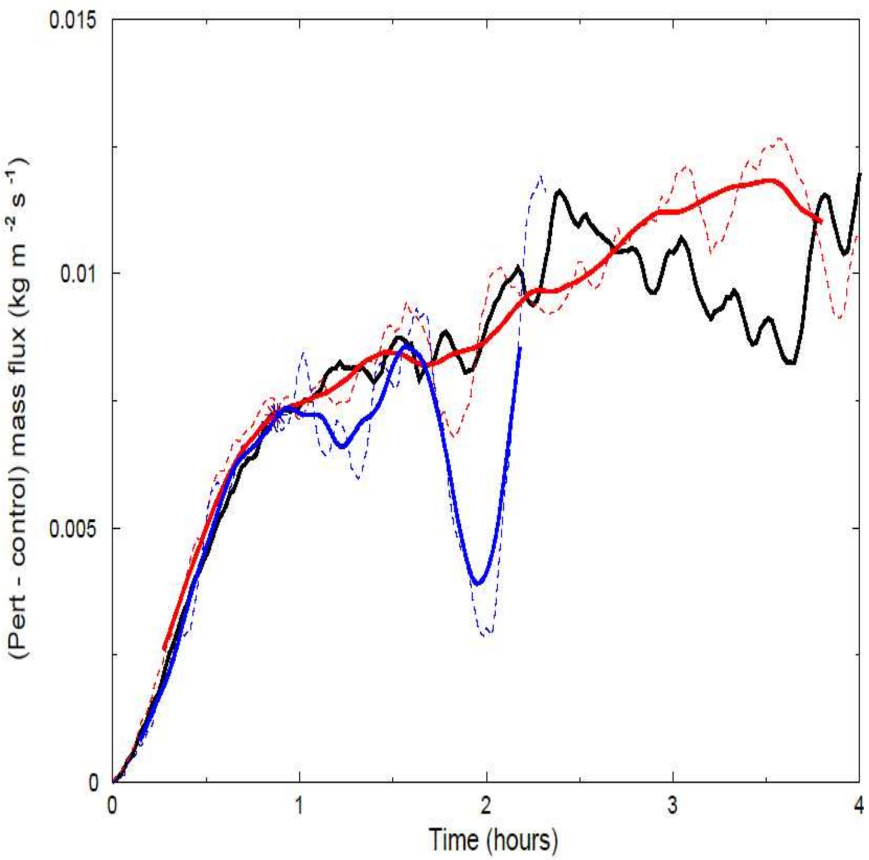
Closure I

- CAPE closure based on full ensemble of clouds
- CAPE removed with a closure timescale that varies with forcing

$$\tau = k\langle\text{cloud separation}\rangle = k\delta x\sqrt{\frac{\langle m\rangle}{\langle M\rangle}}$$

- Tolerant of weak forcing
- Acts aggressively to remove large instability

Adjustment Timescale



Time scaled by cloud separation

- Closure timescale equivalent to adjustment timescale if forcing removed
- Rapid response governed by gravity wave propagation between clouds
- (Slower evolution of moisture variables)

Closure II

- $\langle M \rangle$ depends only the large-scale state
- Local calculations appropriate only if no sub-grid fluctuations
  - Leads to amplification of any artifical local fluctuations in deterministic mass flux scheme
- Averaging region should contain many clouds

SCM Tests

Tests of scheme

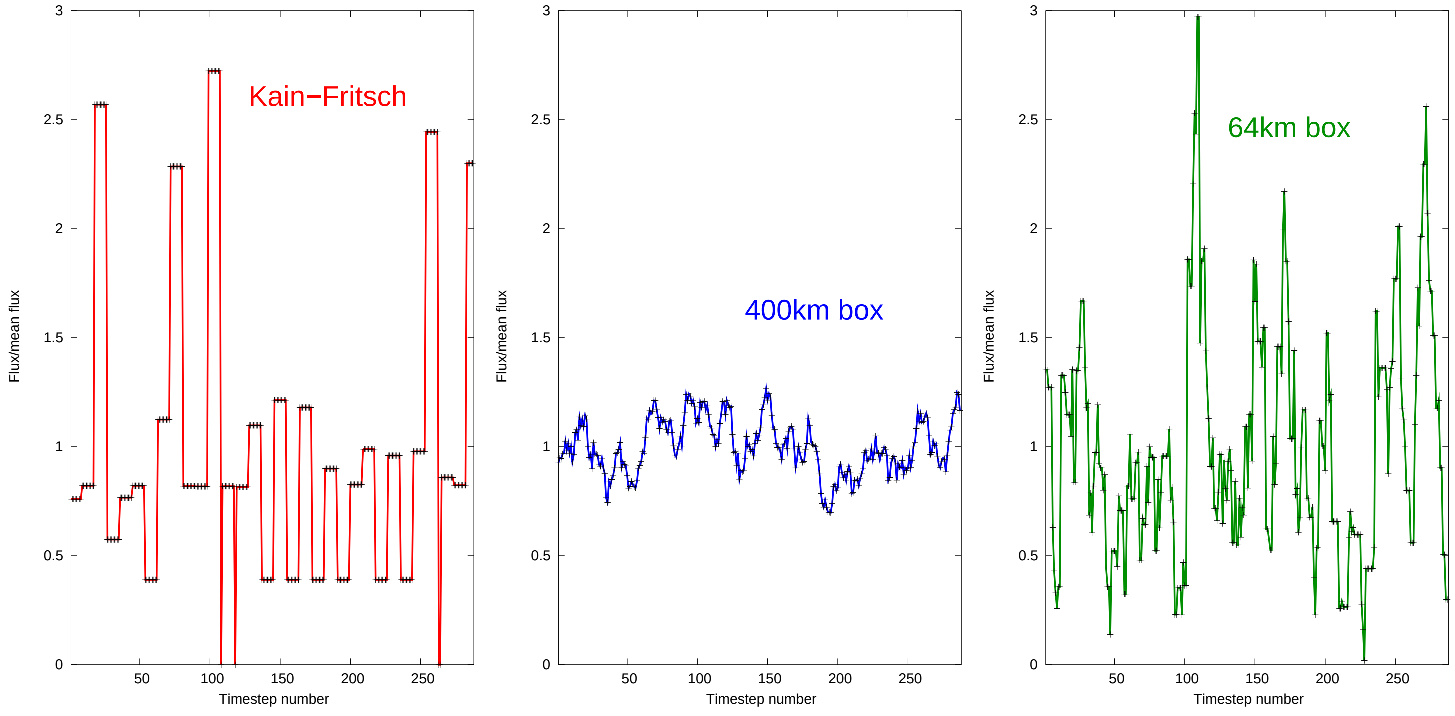
Met Office Unified Model – single column version

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

Aim is to replicate mean state and fluctuations of a companion CRM simulation

Physical not Numerical Noise

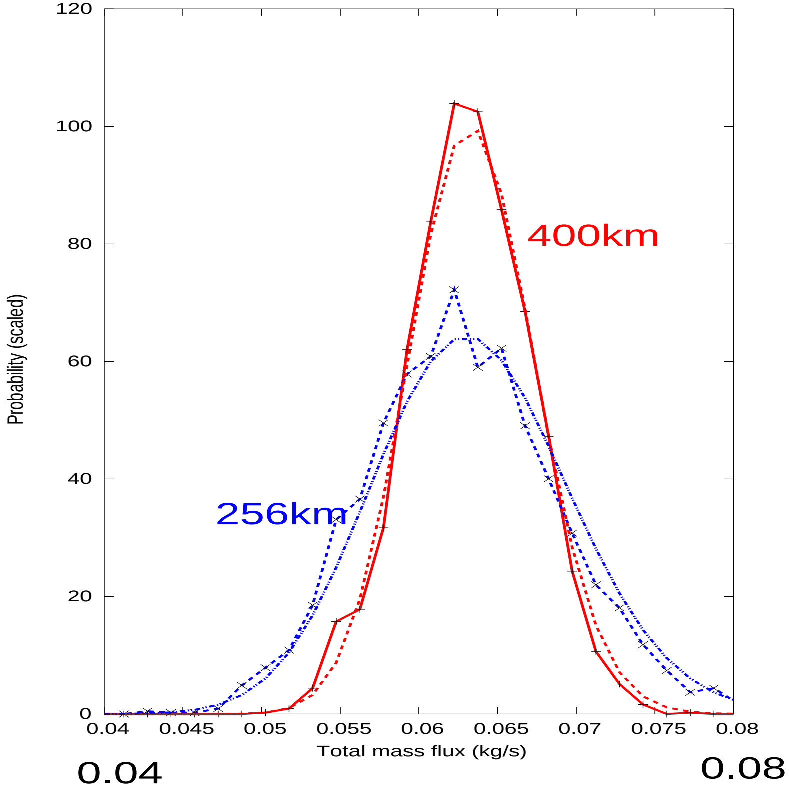
Does a steady forcing give a steady response (deterministic limit of a large grid box)?

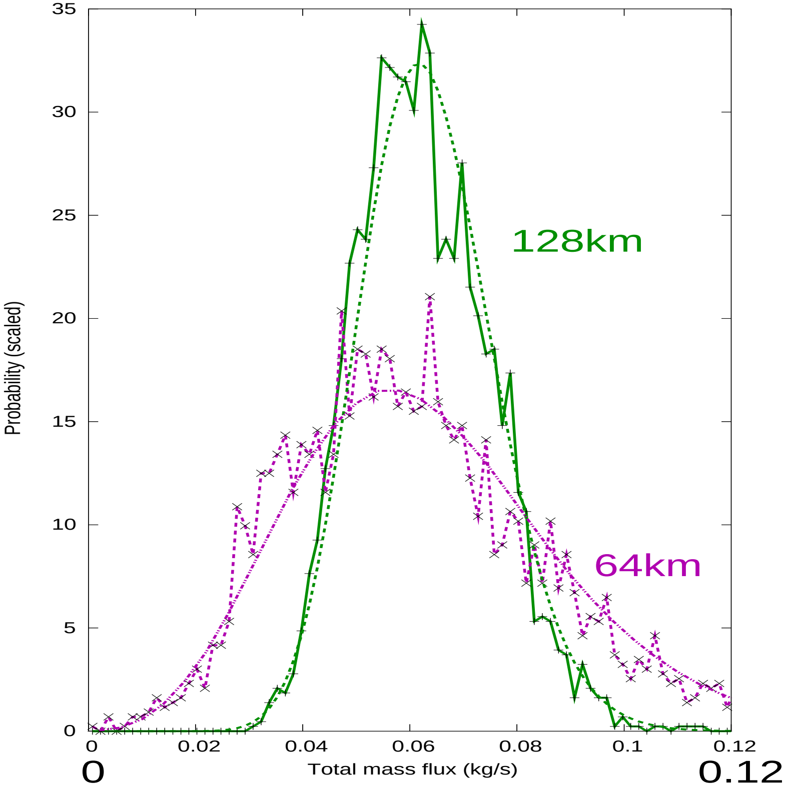


1 'cloud' $\sim$ 200 clouds $\sim$ 5 clouds

Distribution of M

Is the desired distribution of M obtained for finite-sized grid boxes?





Realistic Mean State

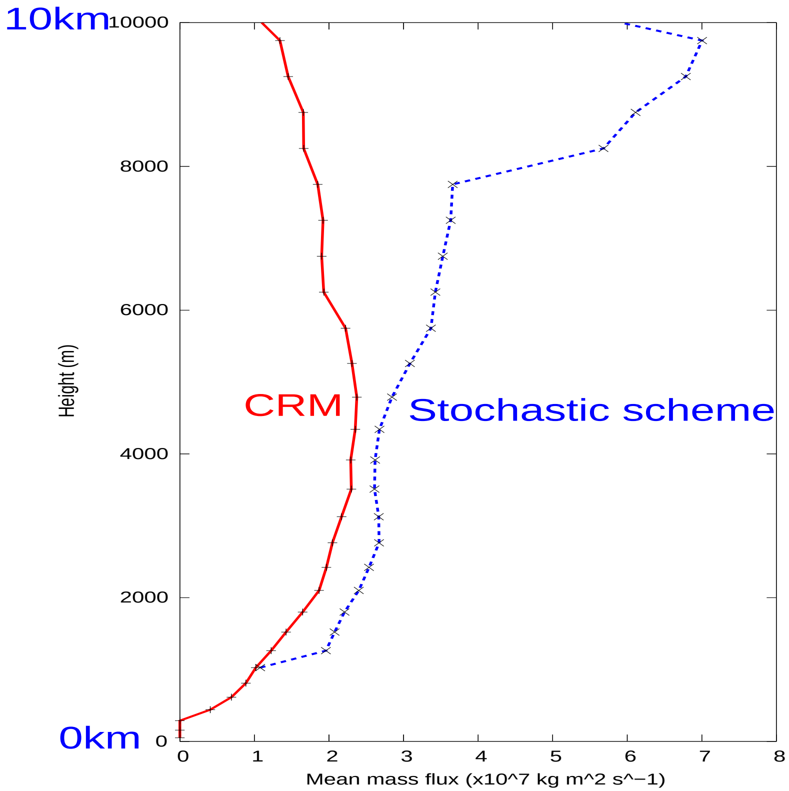
Mean state temperature and humidity profiles sensible (not worse than Kain-Fritsch)?

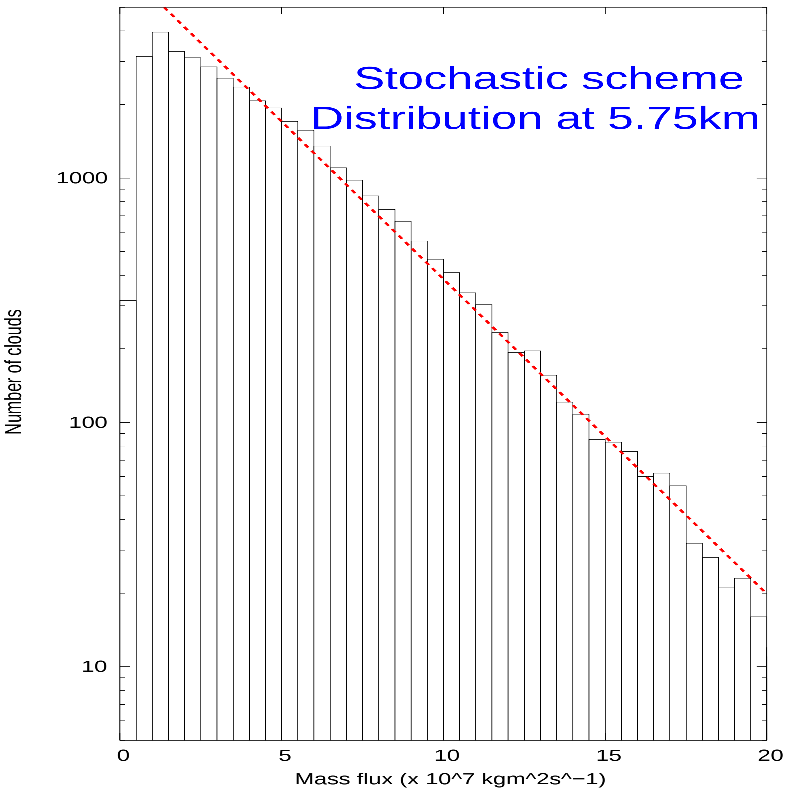
- Differences between SCM states and the CRM state are comparable to differences between CRMs.
- Fluctuations do not shift mean state (shouldn't in 1D!)

Cloud Properties

Are properties of the individual clouds sensible?

$\langle m \rangle \sim$ constant with height, exponential distribution?





Future Steps

1. Implementation in full UM (non-trivial as non-local)
2. Implementation in DWD Lokal Model (regional NWP model)
3. Tests in COSMO-LEPS ensemble system, to include cases from CSIP
4. Dependencies of cloud lifetime (size and forcing) from tracking experiments in CRMs
5. Relax (or remove) equilibrium assumption?
   (with Laura Davies and Steve Derbyshire)
6. Longer term ensemble tests
7. Aqua-planet global UM