Stochastic Convective Parameterization with Multiple Plumes

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Case for a Stochastic Scheme

Because determinism is...

...fundamentally unrealistic...

A determinstic scheme aims to find the ensemble mean effect of the sub-grid states on the resolved flow. However, variability arises naturally in convection because instability is released by discrete cumulus clouds. Even averaging up to climate resolution, CRMs show that a wide range of sub-grid states are possible with fluctuations about the mean remaining a prominent feature of the system.

... and a seriously flawed approximation in practice.

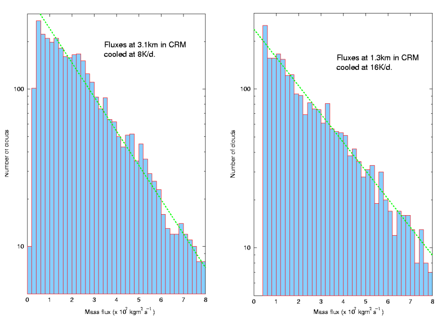
Determinism eliminates important physical interactions between sub-grid fluctuations and resolved motions. Missing convective variability is a serious problem, damaging the ability of models to capture important low-frequency, large-scale features. It contributes to the insufficient spread of ensemble forecasts and to the insufficient variability in GCM tropical climates, which (for example) impacts on their ability to represent the QBO.

How It Works

An ensemble of weakly-interacting convective cells in statistical equilibrium has a pdf of mass flux per cloud that is exponential (Cohen and Craig 2002),

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

Here m is the mass flux of a single cloud, N is the total number of clouds and angled brackets denote ensemble averages. The distribution is remarkably robust in CRM simulations of radiative-convective equilibrium.



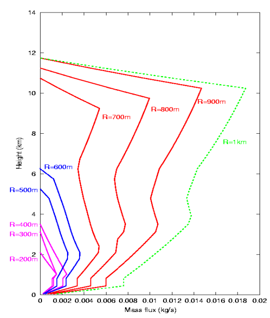
Log-linear histograms of cloud mass fluxes in CRM simulations of radiative-convective equilibrium. Best fit lines for exponentials have been added. (The truncation for the smallest clouds is numerical in origin.)

The spectral representation becomes stochastic on recognizing that the typical number of clouds in a grid box need not be large. Hence, it is important to account for the quantization of mass flux into individual clouds. Our stochastic parameterization launches convective plumes randomly, with the above distribution of fluxes being imposed at the LCL.

Each plume is parameterized as a distinct entity, and may persist for multiple timesteps (a lifetime of 45min). A 1D plume model describes each cloud: specifically we use the entraining plume model from the Kain-Fritsch (KF) scheme (Kain, 2004). The equation

$$m = \frac{\langle m\rangle}{\langle r^2\rangle}r^2$$

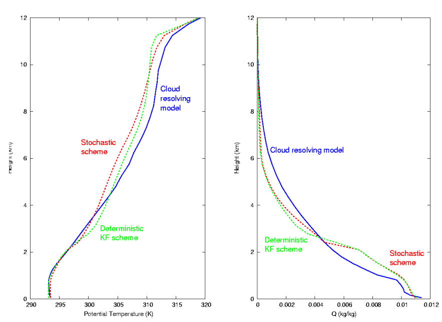
converts the pdf above into a pdf of radii. The radius controls the entrainment rate and its variation can produce different types of plume, from shallow to mid-level to deep convection. This enables a spectrum of plumes to reproduce actual mass flux profiles much more effectively than any single plume.



Examples of mass flux profiles for plumes of different radii launched into the same environment. The 1km plume is that which would be used by the standard KF scheme.

Testing the Scheme

We have tested the scheme in radiative-convective equilibrium using the UM single column model (SCM). The aim is to replicate in a statistical sense the behaviour of a CRM subject to the same imposed forcing. It is interesting also to compare the stochastic scheme with the standard KF parameterization. Similar mean equilibrium states can be achieved, although the KF performance is very sensitive to the temperature perturbation that it requires as a triggering device.



Equilibrium profiles of potential temperature (left) and water vapour (right) in radiative-convective equilibrium.Using the KF scheme a temperature perturbation of 0.05K was applied as a triggering device.

Although the stochastic scheme imposes an exponential at the launch level, distributions for other heights are not specified. In practice, however, the mean mass flux profiles agree well with the CRM and exponential distributions appear at other levels.

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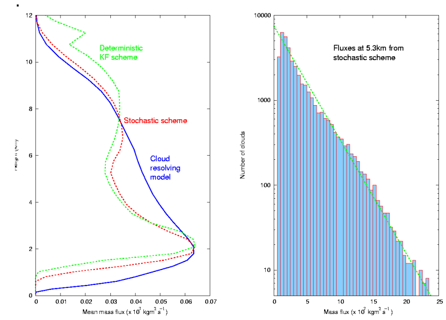
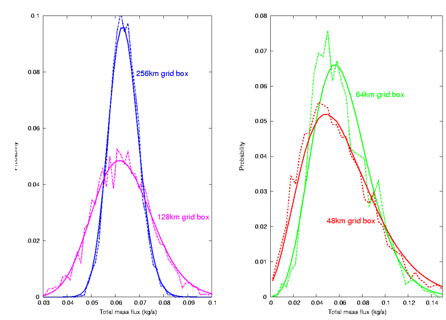


In radiative-convective equilibrium, mean mass flux profiles are shown on the left and the log-linear spectrum produced by the stochastic scheme at 5.3km is shown on the right. An exponential best fit line has been added.

Fluctuations About Equilibrium

The deterministic KF scheme has an unrealistic trimodal pdf for the total flux representing no, shallow and deep convection (a deep plume is present ~35% of the time). By contrast, the number of cumulus elements in the stochastic scheme can vary significantly. Variance increases considerably as the SCM grid box area decreases, in accordance with both CRMs and theory (Cohen and Craig 2002). Thus, our scheme adjusts itself to model grid length in a natural and automatic way.



pdfs for the total mass flux, *M*, obtained from the SCM (dotted) and from theory (solid) for various grid-box areas.

Closure

We are currently investigating a CAPE closure method for determining the ensemble mean mass flux of the full cumulus field, $\langle M\rangle=\langle N\rangle\langle m\rangle$. Assuming equilibrium, we require that the action of the full ensemble for one cloud lifetime consumes 90% of the dilute, ensemble CAPE. Note that the equilibrium holds only on the large scale. It is not valid to perform closure calculations on instantaneous, local profiles since this would introduce artificial variability. The closure therefore uses a profile averaged sufficiently to contain many clouds and smooth out convective fluctuations. This equilibrium scale is itself dependent upon the forcing (the averaging distance scales on the mean inter-cloud separation).

References

Cohen and Craig (2002). JCMM Report 137.
Kain (2004). *J. Appl. Meteorol.* **43**, 170.

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