STOCHASTIC CONVECTIVE PARAMETERIZATION WITH MULTIPLE PLUMES

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1. CHARACTER OF THE SCHEME

We have produced a stochastic parameterization of cumulus clouds, suitable for use at both climate and NWP resolutions. The scheme does not relax model profiles towards an assumed state, but attempts to represent cumulus elements directly (as in Gregory and Rowntree, 1990; Kain 2004). Unlike many such schemes, however, its conceptual basis is not some "representative plume", nor an "ensemble plume" obtained from a weighted sum over a variety of cloud types. Rather, the approach encompasses a variable number of plumes, each plume being launched randomly with properties selected from a pdf. In the deterministic limit where there are very many plumes present, our method is equivalent to a true spectral scheme, as envisaged by Arakawa and Schubert (1974).

2. THE CASE FOR A STOCHASTIC SCHEME

The need for stochastic representations of parameterized small-scale flows has been increasingly recognized over recent years. The argument stems from the manifest difficulties of trying to struggle along without them. Determinism is fundamentally unrealistic, and is also a seriously flawed approximation in practice.

2.1 Determinism is Unrealistic

A deterministic scheme takes as input the instantaneous resolved-scale flow and produces as a unique output the feedbacks to that flow from the sub-grid convective motions. However, an element of small-scale variability arises naturally in convection because instability is released by discrete cumulus clouds, with some distribution of sizes. It is straightforward to demonstrate explicitly that the convective states consistent with resolved flows are wide-ranging. Figure 1 shows the distribution of updraft mass fluxes near cloud base that were obtained from a cloud-resolving-model (CRM) simulation (Cohen, 2001) of radiative-convective equilibrium. The fluxes are averaged over various areas, representative of possible grid-box sizes in a larger-scale model.

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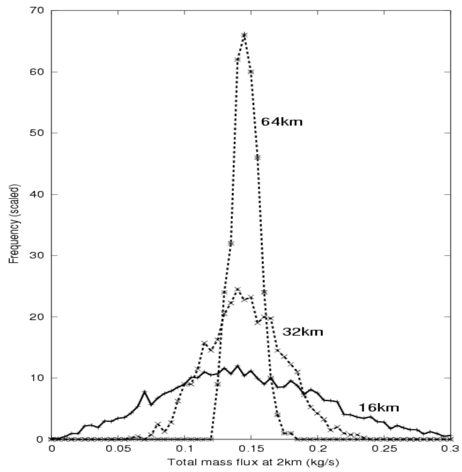

Figure 1. Histogram of total convective mass flux obtained from a CRM simulation. The total flux is averaged over different-sized areas and binned into intervals of 0.01kg/s. The vertical axis is scaled to account for the larger number of suitable averaging areas that become available as the unit averaging area is reduced in size.

Even with strong and uniform forcing, there is considerable convective variability at a mesoscale gridlength of 16km. At a global resolution of 64km, one might hope that the increased averaging would reduce the variability to tolerable levels. However, the width of the pdf is still $\sim$30% of the mean flux, so that fluctuations about the ensemble mean remain a notable feature of the system.

2.2 Determinism is a Problematic Approximation

A deterministic scheme aims to determine the ensemble mean effect of the sub-grid states. Thus, it neglects convective fluctuations, which as we have seen, are potentially large. Moreover, the fluctuations are capable of interacting strongly with non-linearities in the convective system and with model dynamics. It is clear that the missing convective variability is a serious problem that cannot simply be dismissed. There are good indications that the lack of high-frequency, small-scale variability damages the ability of numerical models to capture important low-frequency, large-scale features of interest. Variations in moist convection are known to provoke mesoscale simulations to evolve in qualitatively diverse ways (Zhang et al., 2003). However, variations in the initial conditions are often not able to produce ensembles with sufficient spread. Similarly, there is a systematic tendency to produce insufficient variability in many aspects of GCMs, particularly in the tropics. Insufficient variability has been implicated in the inability of models to predict features such as the equatorial quasi-biennial oscillation (Horinouchi et al., 2003).

3. A PHYSICALLY-BASED STOCHASTIC SCHEME

A number of groups have investigated parameterizations with a stochastic element (e.g., Buizza, 1999; Majda and Khouider, 2002; Lin and Neelin, 2003). Results have been encouraging, demonstrating positive impacts for a variety of approaches. However, an obvious objection to current stochastic schemes is the rather arbitrary character of the variability introduced. Justifications for particular schemes are no stronger than appeals to plausibility. We contend that the benefits of stochastic representations are now demonstrated, and so we should look beyond toy models. Small-scale variability included in models should have as much solid physical support as is possible, and our scheme is designed with this consideration to the fore.

3.1 Outline of Scheme

Exploiting an analogy with the ideal gas, Cohen (2001) showed that an ensemble of weakly-interacting convective cells in statistical equilibrium has a pdf of mass flux per cloud that is exponential,

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

Here *m* is the mass flux of a single cloud, and the angled brackets denote ensemble averages. The distribution has been verified in CRM simulations of radiative-convective equilibrium. It is remarkably robust, the exponential shape holding for a wide range of forcings and over most of the troposphere.

In our stochastic parameterization, we launch convective plumes with the above distribution of fluxes imposed at the LCL. The assumptions leading to the exponential distribution include a statement of equilibrium that enables one to link the destabilizing forcing mechanisms with the convective response. The strength of the response is can be characterized by the ensemble mean mass flux of the full cumulus field, $\langle M \rangle = \langle N \rangle \langle m \rangle$, where $\langle N \rangle$ is the mean number of cumulus elements present. $\langle M \rangle$ is a normalization factor that can be regarded as some function of processes operating on the large scale. It is calculated with a CAPE closure method, in which the CAPE is based on the full ensemble of entraining plumes. The closure itself operates on an equilibrium spatial scale that is dependent upon the forcing (it uses an averaging distance related to the mean inter-cloud separation).

Each individual convective plume is parameterized as a distinct entity, which may persist in the model over multiple timesteps. We must specify the properties and behaviour of each plume, given *m*, the mass flux at the LCL. A one-dimensional plume model is required for this purpose. We use the plume model of the Kain-Fritsch scheme (Kain, 2004): this contains a buoyancy sorting algorithm and has been chosen because it is designed to be responsive in a realistic way to details of its environment. Thus, when used in a stochastic framework, it allows convective fluctuations in the history of the local environment to influence the properties of individual plumes at the present time. The plume model is linked to the stochastic pdf by assuming that the plume radius is proportional to the square root of the randomly-chosen mass flux. The radius parameter of the plume model is a controlling factor in the entrainment calculations.

4. 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 the CRM subject to the same forcing. A variety of results from the tests will be presented at the conference. Here we outline some of the salient points, contrasting the stochastic scheme with the standard, deterministic, implementation of the Kain-Fritsch scheme, which has only a single cloud type with a single radius.

Similar mean equilibrium states are achieved. However, the number of cumulus elements present in the stochastic scheme fluctuates significantly around a mean of ~30, for a nominal grid-box size of 128km. Of course, this number scales with the grid-box area. By contrast, regardless of the grid size, the original Kain-Fritsch parameterization gives a single plume, which is present around 50% of the time. A pdf of the total mass flux $\langle M \rangle$ produced by the stochastic scheme is shown in Figure 2. This is in good agreement with both theory (Cohen, 2001) and the pdf found in the CRM (not shown). By contrast, the pdf for a deterministic scheme has a spike at zero flux (no plume present), together with an extremely narrow spike at some fixed value of flux (plume present, with weak spread from variations in the environmental conditions).

The mass fluxes above the LCL are unconstrained and there is no reason a priori to expect the stochastic scheme to agree with details of the CRM. However, some agreement is obtained, and in particular, exponential mass flux distributions have been achieved at other heights.

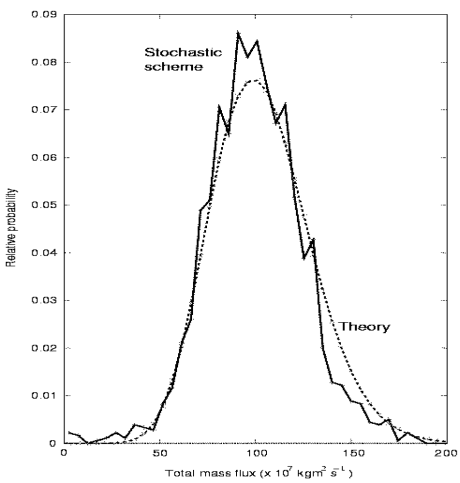

Figure 2. Pdf for the total mass flux, *M*: theoretical result and distribution in the SCM from the stochastic scheme.

5. CONCLUSIONS

We have constructed a stochastic convection scheme, which introduces grid-scale variability in a form that has a sound physical basis. The character of the variability is both verifiable and verified. Single-column tests have shown that the scheme can produce a good representation of the mean convective state and the statistical variations about that state. We are currently exploring the behaviour of the scheme in a full 3D model.

6. ACKNOWLEDGEMENTS

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