A new convection scheme using a simple closure

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Introduction

The parameterization of cumulus convection remains a major problem for general circulation models (GCMs), even after several decades of research. Most schemes incorporate a saturated updraft plume, but resort to a variety of fairly arbitrary closures to determine an effective mass flux, or amount of environmental stabilization, during a time step. Well-known schemes include the Kuo (1974) scheme, which apportions the moisture convergence each time step, the Arakawa and Schubert (1974) scheme which minimizes a cloud work function, and schemes such as that of Fritsch and Chappell (1980) which minimize convective available potential energy (CAPE). The scheme described in this presentation is also based on an effective grid-square-averaged saturated updraft plume. The closure which determines its mass flux is based entirely on feedback to the environment and the sub-cloud layer, the mass flux being the minimum value which is able to suppress the potential convective activity.

The scheme has been developed within the CSIRO conformal-cubic atmospheric model (C-CAM), whose framework was described by McGregor and Dix (2001). This is an atmospheric GCM, which is being used at CSIRO in both quasi-uniform and variable-resolution configurations, employing the Schmidt (1977) transformation. Examples showing the behaviour of the new convection scheme will be presented, using C-CAM in several configurations.

Description of the new parameterization

The cumulus scheme assumes that in each grid square there is an upward mass flux within a saturated aggregated plume, with compensating subsidence of environmental air outside the plume. This basic framework was proposed by Ooyama (1971) and adopted by Arakawa (1969); the same assumption is adopted in the Arakawa-Gordon scheme, as described by McGregor et al. (1993), and used extensively in simulations with the CSIRO Mk2 GCM and the Division of Atmospheric Research Limited Area Model (DARLAM). The parameterization is formulated in terms of the dry static energy,

$$s_k = c_p T_k + g z_k$$

and the moist static energy

$$h_k = s_k + L q_k,$$

where T, q, z and k are respectively temperature, moisture mixing ratio, height above ground, and the vertical layer index of the model. The other constants c_p, g and L have their usual meaning.

Cloud base and the criteria for convection

The cloud-base layer is defined here as the almost-saturated layer of air just below the saturated plume. Cloud base is determined by proceeding downwards to find the lowest of any contiguous moist-adiabatically-unstable layers. For this calculation it is assumed that the mixing ratio of the air parcel at the potential cloud base, q^p_{kb}, is the environment value, q_{kb}, enhanced by a factor α, typically set to 1.1; α is designed to represent the sub-grid spatial variability occurring in the boundary layer; q^p_{kb} is capped by the saturated environment value, q^s_{kb}.

The cloud-top layer, kt, is the uppermost layer in which the plume remains saturated. The moist unstable plume satisfies

$$\text{Criterion 1: } h^p_{kb} \geq h^s_k \ for\ kb < k \leq kt.$$

An auxiliary prerequisite for a saturated plume, not guaranteed by Criterion 1, is that the air in the plume should be at least as moist as the saturated environment, at least near cloud base; hence a second criterion is imposed,

$$\text{Criterion 2: } q^p_{kb} \geq q^s_{kb+1}.$$

For convection to occur, it is required that there exists a cloud-base layer, kb, and a cloud-top layer, kt, satisfying both the above equations. Although the cloud-base specification is very simple, it permits a calculation of the new cloud-base conditions as a result of the convective modification of the environment, and hence permits a simple and natural cumulus closure. Alternative lifting-condensation-level methods may end up being no better overall, as they still omit mesoscale enhancement effects such as convective outflows and local advection. Moreover, lifting-condensation-level methods make the unreasonable implicit assumption that below each cumulus cloud there exists a plume connecting it to the earth's surface. Note that it is possible to incorporate more complicated expressions for q^p_{kb} and h^p_{kb}, provided that their convective feedback values can be written as straightforward functions of the convective mass flux, M.

Plume description and subsidence

Saturated air is assumed to enter the (buoyant) plume from the cloud-base level only. No lateral entrainment is included, so cloud top is at the level of neutral buoyancy for a saturated air parcel.

The upward mass flux within the plume is balanced by subsidence of environmental air between cloud top and cloud base. Exact balance of mass flux is imposed each time step at each level within each grid square, also taking into account any downdrafts.

Downdrafts

Downdrafts provide an extra stabilizing process which helps to prevent the occurrence of excessive precipitation events, especially over tropical ocean regions. Downdrafts are allowed to start from a level *kd,* which is presently assigned to be 75% up the height of the plume (pressure-wise) and emerge at cloud-base level. It is assumed that environmental air with mixing ratio q_{kd} is entrained at the top of the downdraft, and that evaporation of the precipitation falling within the downdraft drives the cold downward motion. At the cloud-base level kb, the downdraft is assumed to have mixing ratio q_D, which is saturated at the emerging downdraft temperature T_D. The downdraft air at cloud base thus satisfies

$$T_D = T_{kb} + (s_D - s_{kb})/c_p = T_{kb} + (s_{kd} - s_{kb})/c_p - (q_D - q_{kd})L/c_p$$

and

$$q_D = q^s_{kb} - (T_{kb} - T_D)dq^s_{kb}/dT.$$

Substituting for q_D in the prior equation provides

$$T_D = T_{kb} + \frac{s_{kd} - s_{kb} - L(q^s_{kb} - q_{kd})}{c_p + L dq^s_{kb}/dT}.$$

The downdraft mass flux, M_D, is assigned to be a fraction of the upward mass flux. Specifically, to allow stronger downdrafts from deep cumuli, a tentative downdraft mass flux

$$M_D = 0.6M(p_{kb} - p_{kt})/p_0$$

is chosen, where p_{kb}, p_{kt} and p_0 denote, respectively, pressure at cloud-base, cloud-top and the ground. If the evaporating moisture needed to drive the downdraft is such that the net precipitation would become zero, then the downdraft is completely suppressed. Simulations are found to be not very sensitive to the 0.6 parameter, with alternative values between 0.5 and 0.7 producing fairly similar results.

Detrainment

A simple detrainment scheme is used, in that a fraction, β, of the precipitating moisture condensed within the plume is distributed as liquid water into the environment surrounding the convective plume. In present simulations, $\beta = 0.05$ is chosen. The vertical distribution of moistening is prescribed to increase linearly from zero at cloud base to a maximum at cloud top, representing in a simplistic way the formation of cirrus layers. Alternative vertical distributions could be readily incorporated. For the simulations shown in this talk, the liquid water scheme is not yet activated, so the detrained liquid water is immediately evaporated into the environment at the detrained level.

Closure

The above processes provide a modification of the environmental temperatures and moistures for each level, with changes proportional to the (as yet undetermined) mass flux. The basic closure is that convection continues to exhaustion during the model time step. Exhaustion occurs for the smallest possible mass flux such that the modified environment no longer provides a cloud-base parcel at level kb, which is still moist convectively unstable for all cloud layers up to level kt. The cumulus convection closure is simply that the mass flux be the minimum flux which will violate either Criterion 1 or 2, for the current cloud-base and cloud-top levels, during a single time step. Criterion 2 for moisture often turns out to be a stronger constraint than Criterion 1. The calculation at this stage corresponds to a "hard" convective adjustment.

Multiple plumes and relaxation time

In any model time step, Δt, two passes of the convection scheme are performed, primarily to avoid the possibility that either the cloud-base or cloud-top layers are only marginally satisfying the convective stability criteria. For the first pass the calculated mass flux is boosted by 2%, to ensure that the same kb and kt are not used for the second pass. Extra passes can be performed if desired. Usually the second pass produces little extra effect.

To cater for a small model time step, the net effects of convection are modified after the second pass by means of a convective relaxation time, τ, usually set at 1200 s, providing a "soft" convective adjustment for model time steps less than τ. Note that if a very small model time step is used, together with "hard" adjustment, then convection schemes will tend to produce a sequence of fairly shallow clouds as the convective instabilities are instantly removed. The convective relaxation time is implemented by multiplying the effects of convection by a factor $\Delta t/\tau$, provided that $\Delta t < \tau$.

Shallow convection

Shallow convection is a problematic area. It is possible to attempt to treat shallow convection by using the above framework, for example by detraining and re-evaporating all the derived precipitation for clouds less than around 200 hPa deep. However, subsidence will still act to dry and heat environmental layers, and can easily overwhelm the moistening/cooling effect of the detrained moisture. This can lead to unnaturally stable low-level layers (around 850 hPa).

In reality, shallow convection often has the appearance of Benard cells, or other horizontally-organized patterns, rather than discrete plumes. For the present, a version of the enhanced vertical-diffusivity scheme of Tiedtke (1984) has been incorporated. This scheme is activated for low-level relative humidities greater than 80%, through depths where the low -level saturated moist static energy exceeds the saturated values of layers above. The scheme is only activated if the top of the shallow convection implied by this procedure does not go above 750 hPa. The deep convection scheme is only activated if the cloud-top layer is above 800 hPa; deep convection is performed before shallow convection.

Computational efficiency

The scheme is readily vectorized, and achieves a speed of about 1800 MFlops on the NEC SX5 computer. Together with the calculation of resolved precipitation and its evaporation, the scheme takes about 5% of the total computational time for a typical climate simulation

Simulations using the new parameterization

A variety of simulations will be shown during the presentation. Validation of the convective changes made to temperature and moisture profiles will be provided for a variety of points. Results from an AMIP 2 simulation will be shown, using an 18 level version of C-CAM with a C48 grid (6 x 48 x 48 grid points), with initial conditions, sea-surface temperatures (SSTs) and sea-ice distributions provided by National Center for Environmental Prediction (NCEP) reanalyses. Comparisons will be presented between modelled and observed precipitation, cloud amounts and moisture profiles.

A 10-year simulation will also be shown, concentrating on the Asian monsoon. This used a C63 global grid with a Schmidt stretching factor of 0.37, giving about 60-km resolution over Asia. Initial conditions and SSTs were again supplied by NCEP reanalyses. Throughout the simulation, 3-hourly rainfall was saved and later interpolated linearly to hourly values. This permits a quite favourable comparison of the diurnal rainfall characteristics with the observations of Sorooshian et al. (2002).

Concluding comments

A new cumulus convection scheme with a simple and natural closure has been described in this presentation. The uncertainty present in most closures has been removed, and has been transferred to a degree of arbitrariness in the prescription of the sub-cloud layer. The simple closure is possible because of the ready calculation of environmental and sub-cloud feedback by the cumulus activity. Other attractive features of the scheme include allowance for cold downdrafts, the possibility of including multiple cloud types during a single model time step, and high computational efficiency.

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