1.5 PARAMETERIZED CONVECTION WITH ENSEMBLE CLOSURE/FEEDBACK ASSUMPTIONS

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1 INTRODUCTION

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Properly parameterizing the effects of convection is still a challenging problem for numerical weather prediction (NWP) applications. There are many different parameterizations for deep and shallow convection that exploit the current understanding of the complicated physics and dynamics of convective clouds to express the interaction between the larger scale flow and the convective clouds in simple "parameterized" terms. This "parameterization problem" gets even more complicated as the horizontal resolution in NWP models increases to scales in which a clear scale separation no longer exists. These "gray scales" for convective parameterizations are scales on which next generation NWP models like the Weather Research and Forecast (WRF) model will be widely applied.

The introduction of environmental applications such as atmospheric chemistry into next generation NWP models may be an additional complication for convective applications. Assumptions that are of lesser importance for meteorological simulations (some up to now maybe totally neglected) could be of great importance for chemistry applications. In a consistent "online" employment, the treatment for both meteorological as well as chemical applications should be the same. While this may require the introduction of more degrees of freedom into the different schemes, it may also be a great opportunity to uncover errors in convective parameterizations that previously were difficult to detect.

In this work we discuss some of the existing meteorological parameterizations of convection, and introduce a new convective parameterization that draws from the existing schemes by employing an ensemble of various closure assumptions.

This parameterization is currently being used in the 20km Rapid Update Cycle (RUC) model (Benjamin et al. 2001) and has shown strong improvement in precipitation forecasts for the RUC (Schwartz and Benjamin 2001).

2 THE "BASIC" CUMULUS PARAMETERIZATION

This is a simple scheme that is based on a convective parameterization developed by Grell (1993) and discussed in more detail by Grell et al. (1994). For our application it was modified to include effects of entrainment/detrainment around the updraft/downdraft edges, as well as an ensemble of different closure assumptions. In addition it was coupled to the explicit prediction of precipitation through detrainment of cloud water and ice around the cloud edges and at the cloud top. Following Grell (1993), we will use the same terminology of dynamic control (the modulation of the convection by the environment), feedback (modulation of the environment

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by the convection), and static control (the cloud model that is used to determine cloud properties). Because of the limited scope of this paper we will refrain from equations as much as possible. However, the dynamic control is described in a bit more detail, since it uses the fundamentally most different ensembles.

2.1 *Dynamic Control*

Many different closures exist in the literature to determine the amount and location of convection. Here we test an ensemble of such closures to determine m_b, the cloud base mass flux. We first begin by describing a subset of closures that may be used by our parameterization to determine m_b.

The first type of closure is based on some type of stability equilibrium. They use the definition of the cloud work function which was first defined by Arakawa and Schubert (1974). In short, using the time change of the cloud work function (A), which is an integral measure of the buoyancy force associated with a cloud, an equation can be derived to calculate the cloud base mass flux m_b which takes the form

$$\frac{dA}{dt} = \left(\frac{dA}{dt}\right)_{NC} + \left(\frac{dA}{dt}\right)_{CONVN} m_b, \qquad (1)$$

Here subscript NC represents changes due to effects other than convection, and subscript $CONVN$ represents changes due to convective clouds, normalized by cloud base mass flux m_b. In the original implementation of the Grell scheme (Grell et al. 1994), as well as in Arakawa-Schubert implementations (Arakawa-Schubert 1974, Lord 1978, Lord 1982, Grell 1993), it was assumed

$$\left(\frac{dA}{dt}\right)_{NC} \equiv F \gg \frac{dA}{dt} \qquad (2)$$

F is usually termed the "large scale forcing". However, by using subscript NC we indicate that F can include any type of forcing other than changes by the convective parameterization. F is not restricted to grid scale forcing terms, such as advection. In the numerical model its calculation is extremely simple, using

$$F = \left(\frac{dA_{tot}}{dt}\right)_{NC} = \frac{A' - A}{dt}, \qquad (3)$$

where A' is the value of the cloud work function that was calculated using thermodynamic fields after modification by model tendencies (advection as well as subgridscale PBL and radiation tendencies). In the original Grell (1994) implementation, A was calculated using thermodynamic fields at a particular time. In a more Arakawa-Schubert type implementation, A would simply be a climatological value. The second term on the right hand side of equation (1) is calculated using

$$\left(\frac{dA}{dt}\right)_{CONVN} \equiv K = \frac{A'' - A}{m_b' dt}. \qquad (4)$$

Here A'' is calculated using thermodynamic fields that have been modified by an arbitrary unit mass (m_b') of cloud, and cloud properties that were calculated using the static control. m_b is then simply given by

$$m_b = -\frac{F}{K}.$$

In a second implementation, to simulate a closure in which the stability is simply removed by the convection (as assumed in similar form by Fritsch-Chappel (1980), Kain-Fritsch (1992), Kreitzberg-Perkey (1976)), we simply assume

$$F = -\frac{A}{dtc}, \qquad (5)$$

which has the effect of making m_b strong enough to remove the available instability within the specified time period dtc. Naturally (5) is sensitive to the choice of the parameter dtc.

Another group of widely used closure assumptions is based on moisture convergence (Kuo 1965, Kuo 1974, Anthes 1977, Molinari 1982, Krishnamurti et al. 1983, to name a few). While there are many different choices, here we chose an assumption first introduced by Krishnamurti et al. (1983), where the total rainfall is assumed to be proportional to the integrated vertical advection of moisture (M_{tv}), which is defined as

$$M_{tv} = \int \omega \left(\frac{\partial q}{\partial p} \right) dp. \quad (6)$$

and

$$R = M_{tv}(1 + f_{emp})(1 - b) \quad (7)$$

Here b is the Kuo moistening parameter, and f_{emp} is an empirical constant.

A further dynamic closure that is easily implemented was first introduced by Brown (1979), who assumes

$$m_u(l_t) = \frac{a}{g\tilde{\omega}(l_t)} \quad (8)$$

where a is an empirical constant, ω the larger scale vertical motion, m_u the updraft mass flux, and l_t is some lower tropospheric level, such as the top of the PBL height, or the level of the updraft originating air.

This closure was modified by Frank and Cohen (1987), by assuming

$$m_u(l_t) = \tilde{M}(l_t) - m_d(l_t, t - \Delta t) \quad (9)$$

Here $\tilde{M}$ is the mass flux of the larger scale environment, and $m_d(l_t, t - \Delta t)$ is the downdraft mass flux at the previous time step. This closure simulates a time lag between updraft and downdraft, envisioning the downdraft of a thunderstorm forcing another updraft at a later time.

3 CHOICE OF ENSEMBLES

Table 1 shows a summary of a typical choice of ensembles for our study. This particular set includes 288 different versions of the cumulus parameterization. Although this is equivalent of calling the convective parameterization at every grid point and at every time step 288 times, the actual cost is much smaller, since most parameters can be varied at very low levels.

Table 1: Overview of ensembles used in this study

name	part of parameterization	varied parameter	# of variations	specifics variations
dyn1	dynamic control	quasi equilibrium	2	$A = A(t_0)$ $A = A(cl)$
dyn2	dynamic control	removal of instability	2	$dtc = 30mn$ $dtc = 40mn$
dyn3	dynamic control	moisture conv	2	$b = 0$ $b = \beta$
dyn4	dynamic control	low level mass flux	2	2 different levels
st1	static control	downdraft strength	6	perturb around optimal
num1	numerics	$m_b\prime$	6	see text

The main focus of this paper is the exploration of choices that lead to different solutions for m_b. As a consequence we opted to choose assumptions of the dynamic control as the largest ensemble, and test at least 8 different closure assumptions. Ensemble dyn1 uses 2 different implementations of some type of stability equilibrium assumptions that were described above. Ensemble dyn2 uses the assumption that the instability is removed within a specified time period and varies that time period (dtc in equation 5). In dyn3 the vertical advection of moisture is used as a closure. Both variations of this closure assume $f_{emp} = 0$, but vary the Kuo moistening parameter b.

Finally, in dyn4 we add a low-level mass flux closure, as proposed by Brown (1979) and also in a different version by Frank and Cohen (1987).

Because of previous results in regional/local climate simulations (Grell et al. 2000), we opted to make m_d in (9) also dependent on the movement of convection, by assuming

$$m_u(l_t) = \tilde{M}(l_t) - m_d(l_t, t - \Delta t, upstream) \quad (10)$$

The direction of movement was simply defined using the pressure weighted mean wind direction between the pressure level of 300 mb and about 150 mb above the surface.

In addition to the dynamic control, we also wanted to add some ensembles that test assumptions of the static control and feedback, to which the parameterization is very sensitive. One of the most sensitive parameters is generally the precipitation efficiency β, which strongly influences the strength of the downdraft. This parameter is usually calculated using a method that was originally proposed by Fritsch and Chappel (1980), which makes the precipitation efficiency wind-shear dependent. Here we first chose an optimal value for β, using the Fritsch and Chappel (1980) dependence. We then perturb β in increments of $\frac{1-\beta}{nu}$, with nu being the total number of ensemble members for this ensemble.

The different choices in closure assumptions may result in a large range of cloud base mass fluxes m_b. To calculate the normalized change of the cloud work function in equation (4), the choice of an arbitrary unit mass flux $m_{b'}$ is necessary. While the parameterization is usually independent of a particular value for $m_{b'}$, it should be chosen small, yet not too small to avoid round-off errors (Lord 1978, Grell 1993). Because of the larger variation in cloud base mass fluxes m_b we decided to add an ensemble and vary $m_{b'}$ in increments of 10% around its original value.

4 ENSEMBLE STATISTICS

Cumulus parameterization ensemble statistics were generated and evaluated in order to estimate the statistical properties of ensembles from individual parameterizations and also from unified ensembles. Because grid point and time step ensemble averaging (Wilks, 1995, p. 216.) is the main approach used in our work, each ensemble and subensemble was submitted to statistical analysis using mean (average), standard deviation, skewness, and flatness (curtosis) estimations. These estimations were performed at each time step and at each gridpoint individually. Domain-unified ensembles were also considered. The ensembles were investigated seperately and information was collected about their bias, spread and distribution form.

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