An Approach for Convective Parameterization with Memory: Separating Microphysics and Transport in Grid-Scale Equations

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ABSTRACT

An approach for convective parameterization is presented here, in which grid-scale budget equations of parameterization use separate microphysics and transport terms. This separation is used both as a way to introduce into the parameterization a more explicit causal link between all involved processes and as a vehicle for an easier representation of the memory of convective cells. The equations of parameterization become closer to those of convection-resolving models [cloud-system-resolving models (CSRMs) and large-eddy simulations (LESs)], facilitating parameterization development and validation processes versus a detailed budget of these high-resolution models.

The new Microphysics and Transport Convective Scheme (MTCS) equations are presented and discussed. A first version of a convective scheme based on these equations is tested within a single-column framework. The results obtained with the new scheme are close to those of traditional ones in very moist convective cases [like the Global Atmospheric Research Programme (GARP) Atlantic Tropical Experiment (GATE) Phase III, 1974]. The simulation of more difficult drier situations [European Cloud Systems Study/Global Energy and Water Cycle Experiment (GEWEX) Cloud System Studies (EUROCS/GCSS)] is improved through more memory due to higher sensitivity of simulated convection to dry midtropospheric layers; a prognostic relation between cloudy entrainment and precipitation evaporation dramatically improves the prediction of the phase lag of the convective diurnal cycle over land with respect to surface heat forcing.

The present proposal contains both a relatively general equation set, which can deal continuously with dry, moist, and deep precipitating convection, and separate—and still crude—explicit moist microphysics. In the future, when increasing the complexity of microphysical computations, such an approach may help to unify dry, moist, and deep precipitating convection inside a single parameterization, as well as facilitate global climate model (GCM) and limited-area model (LAM) parameterizations in sharing the same formulation of explicit microphysics with CSRMs.

1. Introduction

Since the 1970s many researchers have endeavored to improve convective parameterization concepts and schemes: the characteristic scale of convective drafts is...
mulus and stratocumulus. Parameterizing convection is a scientific challenge to account for the behavior of an ensemble of convective drafts and its interactions with other processes in a wide variety of environments.

Despite many improvements since the 1970s, current parameterizations still have difficulty in capturing some aspects of convection phenomenology. For example, current GCMs and limited-area models (LAMs) poorly predict the phase of the diurnal cycle in convection over land, as shown by several studies like Yang and Slingo (2001) or Guichard et al. (2004). The representation of the memory of previous convective activity is one difficulty. Current schemes respond to external forcing practically instantaneously, leading to a premature initiation of convection and an erroneous diurnal cycle. More generally, predicting the shallow-to-deep convection transition over land or sea has been a challenge for years, which suggests some fundamental difficulties in physical parameterizations.

As raised by Randall et al. (1997), Mapes (1997, 1998), and Yano et al. (2000), the design of convective parameterization also faces the difficulty of separating convective and nonconvective processes. The usual definition of convection in the meteorological community is very broad, however: Emanuel (1994), for example, defines it as “all circulations which result from the action of gravity upon an unstable vertical distribution of mass.” With this widely used definition, Randall et al. (1997) highlight the fact that many tropical cirrus, which are stratiform-type clouds, originate from previous cumulonimbus anvils and may therefore be considered as convective clouds. Another example is that surface sensible and latent heat fluxes can be enhanced by the effects of cumulus convection (Redelsperger et al. 2000). Should these induced clouds and/or enhanced fluxes be considered part of large-scale forcing, or part of convective response?

These causality issues are raised in convective parameterizations, as long as one defines their role as “estimating convective feedback to nonconvective forcing.” Figure 1 shows a diagram of main interactions between physical processes. Uplifting forces condensation; generated cloud condensates then force other processes, such as autoconversion, accretion, precipitation, precipitation evaporation, and thus downdrafts, which can then force new uplifting, etc. Some of these processes occur at a resolved GCM scale, while others need to be parameterized as being subgrid scale. Our proposal is to define the role of convective parameterizations as “estimating the subgrid-scale rate of convective transport (subgrid-scale motions) and microphysical processes (condensation, evaporation, downdrafts, etc.) as a feedback to resolved forcing.” The causality, intractable in a parameterization when dealing with convec-

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**Fig. 1.** Partition and interaction between physical processes. “Destabilizing processes” increase the CAPE; “triggering processes” decrease the CIN.

- **Destabilizing processes**
  - Adiabatic lifting (frontal, orographic, etc.)
  - Radiation
- **Triggering processes**
  - Near-level convergence
  - Density currents
  - Convective downdrafts
- **Moist convection processes**
  - Buoyant uplifting
  - Condensation
  - Precipitation, evaporation of prec.
  - Autoconversion Accretion

**Destabilizing processes** increase the CAPE; **triggering processes** decrease the CIN.
tion as a whole, then becomes tractable and consists of dealing with interactions between simpler and microphysics-oriented processes, such as those from Fig. 1. To address these two issues—“memory of convective cells” and “causality”—one could therefore be to build a parameterization that would make microphysical terms more explicit so that causal interactions between microphysical processes, such as those in Fig. 1, could be parameterized as such.

This paper is organized as follows. In section 2 an equation set expressed in microphysics and transport, suitable for use in convective parameterizations, is derived from cloud-system-resolving model (CSRM) equations. Section 3 will show the results obtained with a prototype using these microphysics and transport convective scheme (MTCS) equations in a one-dimensional test bed for the Global Atmospheric Research Programme (GARP) Atlantic Tropical Experiment (GATE) and European Cloud Systems Study/Global Energy and Water Cycle Experiment (GEWEX) Cloud System Studies (EUROCS/GCSS). Section 4 will address the specific question of the shallow-to-deep transition, introducing more memory through a prognostic link between precipitation evaporation and cloud entrainment. Section 5 includes the summary and perspectives.

2. From CSRM equations to MTCS equations

The CSRM equations for water vapor \( q \), static energy \( s = c_p T + gz \), and horizontal wind \( (u, v) \) may be expressed in generic form as

\[
\begin{align*}
\frac{\partial q}{\partial t} &= T_q - C + E_C + E_p - (u \cdot \nabla)q \\
\frac{\partial s}{\partial t} &= T_s + R + L(C - E_C - E_p) + H - (u \cdot \nabla)s \\
\frac{\partial u}{\partial t} &= \dot{u}_p - (u \cdot \nabla)u \\
\frac{\partial v}{\partial t} &= \dot{v}_p - (u \cdot \nabla)v
\end{align*}
\]

(1)

where \( T \) is the turbulent source/sink (small eddies); \( C \) is condensation \((\approx 0)\); \( E_C \) evaporation of cloudy condensates \((\approx 0)\); \( E_p \) precipitation evaporation \((\approx 0)\); \( R \) is the radiative source/sink; \( H \) is the heat source/sink due to precipitation (sensible heat exchanges between falling drops and surrounding air; latent heat release due to melting/freezing); and \( \dot{u}_p \) and \( \dot{v}_p \) are the momentum net sources due to pressure force, rotation, and turbulence.

We can derive a simpler system from the one above, relevant for subgrid-scale parameterization, expressing grid-scale tendencies due to subgrid-scale convective processes; this system, called MTCS, is obtained while neglecting, here and for the sake of simplicity, momentum sources and expressing the mean effect of advection as a double flux divergence term [updrafts and environment; in this article, downdrafts will be omitted from equations for convenience, to shorten the equations, as they have a symmetric form like that of updrafts; equations are also presented under the assumption of a small updraft area fraction \( \alpha \ll 1 \), thus replacing environmental values by grid-scale ones):

\[
\begin{align*}
\frac{\partial q}{\partial t}_{\text{conv}} &= -C + E_C + E_p - \frac{\partial \omega^*(q_s - \bar{q})}{\partial p} \\
\frac{\partial s}{\partial t}_{\text{conv}} &= L(C - E_C - E_p) + H - \frac{\partial \omega^*(s_s - \bar{s})}{\partial p} \\
\frac{\partial u}{\partial t}_{\text{conv}} &= -\frac{\partial \omega^*(u_s - \bar{u})}{\partial p} \\
\frac{\partial v}{\partial t}_{\text{conv}} &= -\frac{\partial \omega^*(v_s - \bar{v})}{\partial p}
\end{align*}
\]

(2)

where \( \omega^* \) denotes the bulk mass flux, and \( \psi \) and \( \bar{\psi} \) are, respectively, the cloudy value and the grid-scale value of the variable \( \psi \). The parameterization exercise then consists in formulating \( \omega^* \) and microphysics-related terms.

a. Cloud budget

The grid-scale equation system (2) does not require any stationarity assumption about cloud budgets (water vapor, heat, mass), as these budgets do not appear explicitly in this system. What would occur if one makes such an assumption? The cloud budget can be written as

\[
\begin{align*}
\frac{\partial \sigma}{\partial t} &= -D + E - \frac{\partial \omega^*}{\partial p} \quad \text{(mass)} \\
\frac{\partial \sigma q_s}{\partial t} &= -Dq_s + EQ - \frac{\partial \omega^* q_s}{\partial p} - C \quad \text{(water vapor)} \\
\frac{\partial \sigma s}{\partial t} &= -Ds + ES - \frac{\partial \omega^* s}{\partial p} + LC \quad \text{(heat)}
\end{align*}
\]

(3)

where \( \sigma \) is the updraft fractional area, \( D \) is cloudy detrainment, and \( E \) cloudy entrainment. If one assumes a stationary budget

\[
\frac{\partial \sigma}{\partial t} = \frac{\partial \sigma q_s}{\partial t} = \frac{\partial \sigma s}{\partial t} = 0
\]


one could eliminate, as in Yanai et al. (1973) or Yanai and Johnson (1993), condensation C between (2) and (3); using in addition the stationarity mass budget equation from (3), this would lead to

\[
\begin{align*}
\left( \frac{\partial \rho^* w^*}{\partial t} \right)_{\text{conv}} &= \omega^* \frac{\partial \rho}{\partial \rho} + D(q_c - \bar{q}) + E_C + E_P, \\
\left( \frac{\partial \rho^* q_c^*}{\partial t} \right)_{\text{conv}} &= \omega^* \frac{\partial \rho^* q_c^*}{\partial \rho} + D(s_c - \bar{s}) - L(E_C + E_P),
\end{align*}
\]

(4)

where \( D \) is the detrainment from the equation \( \partial \omega^* \rho^*/\partial \rho = E - D \). The terms \( \omega^* \rho^*/\partial \rho \) and \( \omega^* \rho^*/\partial \rho \) are often referred to as compensating subsidence, as they consist of a vertical advection due to downward motion, which compensates the updraft mass flux \( \omega^* \). The parameterization exercise then consists in expressing \( \omega^* \) and \( D \), where \( D \) contains information about microphysics and part of the transport process. The system (4) is analogous to that used by Yanai et al. (1973) and Yanai and Johnson (1993) to make budgets from observational data. In the wake of Yanai et al. (1973), this approach of a stationarized cloud budget hypothesis has been widely used to develop convective parameterization (e.g., Bougeault 1985; Tiedtke 1989; Gregory and Rowntree 1990; Kain and Fritsch 1990; Bechtold et al. 2001; to name only a few) in deriving different large-scale equations, but sharing the use of this stationarized cloud budget assumption, which renders implicit microphysical terms as detrainment or entrainment terms.

As discussed in the previous section, in the present paper we are seeking to represent convection memory inside our scheme and to render microphysical terms more explicit. For this purpose, one way is to solve (2) and (3) as a whole system using \( \sigma^*, q_c^*, \) and \( s_c^* \) as prognostic variables. Another—and intermediate—prognostic way is to express the “cloudy variables” necessary to evaluate the last terms on the right-hand side of system (2) from entraining plume-type computations with independent treatments for \( \sigma^*, q_c^*, \) and \( E \) that have any chosen degree of prognostic character. Approximations can then be made, leading to a system of equations from which \( D \) does not need to be estimated anymore, thus simplifying the parameterization exercise. In case of a small updraft fractional area the phenomenological link between this simplification and the separation of microphysics and transport terms is quite obvious: the cloud property deviations from the background governing the magnitude of the transport term are only a function of condensation, entrainment, and mass flux. Examples of such an approach for expressing cloudy variables will be presented in sections 3 and 4.

More generally, any convective scheme expressing subgrid-scale convective transport and microphysics terms from (2) with no stationarized cloud budget assumption, in using one or more independent equations to relate cloud properties to resolved state, can be considered as a consistent prognostic-type scheme for which the Yanai et al. (1973) scheme is the equilibrium limit. Some other attempts to introduce memory inside convective parameterizations have been made in the same spirit, such as Pan and Randall (1998) for which the equilibrium limit is the Arakawa and Schubert (1974) scheme, or Gerard and Geleyn (2005) for which the equilibrium limit is the “Control” scheme mentioned later in the present paper. Pan and Randall (1998) and Gerard and Geleyn (2005) differ however from the present proposal, in that they introduced prognostic equations for cloud work function or mass flux with no explicit separation between microphysics and transport in grid-scale equations.

b. Convective types involved

The equation set (2) can deal with a continuous transition from dry convection mass flux transport (thermals, when \( C = E_C = E_P = H = 0 \)) to nonprecipitating convection (cumulus) and precipitating convection (cumulus showers, cumulonimbus precipitation). An important point is that the production of precipitation is performed through the microphysics scheme (autoconversion and accretion) as in CSRM.

c. MTCS system and validation versus CSRM

Initiated by the pioneer work of Gregory and Miller (1989), CSRMs have become an important component to evaluate convective parameterizations in recent years, for example, in Moncrieff et al. (1997) and Siebesma and Cuijpers (1995). The evaluation process is as follows: first, CSRMs are validated against observations; then, convective parameterizations are validated against CSRMs. Clean comparisons are made on fields like Q1, Q2, or Q3 (total physical tendencies of temperature, water vapor, and horizontal wind). However, improving parameterizations also requires further investigation, like separately assessing contributions of cloud dynamics and microphysical processes to Q1, Q2, or Q3.

The latter exercise is difficult to achieve: parameterizations are based on crude assumptions, like that of horizontally uniform saturated updrafts. Comparing such crude drafts to CSRM data requires partitioning CSRM space into cloud and environment. This can be done in many ways, using vertical velocity, occurrence of cloud condensates, buoyancy, etc. Hence, if parameterizations use equation sets like (4) involving pseu-
dosubsidence or detrainment terms, the validation will imply questionable hypotheses on cloud borders. Inversely, what can CSRRMs provide without requiring any additional hypothesis?

1) Transport: Terms like \( \overline{w} q' \), \( \overline{w} \theta' \), \( \overline{w} u' \) can easily be computed from CSRM data with no additional hypothesis.

2) Microphysical terms (condensation, autoconversion, collection, precipitation evaporation, etc.): These terms are computed in CSRRMs from explicitly resolved motions, or partly parameterized motions, but in either case they can be diagnosed separately from transport.

The equations at grid-scale (2) therefore make it possible to compare parameterizations with CSRRMs beyond quantities such as Q1, Q2, or Q3, as rhs terms of parameterizations and CSRRMs now have the same meaning: \( \omega^* \) will obviously not be compared directly to CSRM data since the aforementioned border hypotheses would be required in such a case, but the whole parameterized term \( \partial \omega^*(q_c - \overline{q})/\partial p \) will be compared to \( \partial \omega^* q' / \partial p \) from the CSRM: the microphysical terms \( C \), \( E_C \), \( E_p \), and \( H \) will also be compared individually.

3. A prototype convection scheme based on MTCS equations

a. Coupling microphysics and transport

To build a relevant parameterization from the equation system (2), somehow one needs to couple microphysical terms (\( C, E_C, E_p, \) and \( H \)) with transport terms \( \partial \omega^*(q_c - \overline{q})/\partial p \), where \( \psi \) is a generic variable. In the present prototype we assume condensation and cloudy condensate evaporation to be proportional to the bulk mass flux \( \omega^* \), therefore deriving \( C \) and \( E_C \) from \( \omega^* \) and from quantities per unit of vertical length \( \mathcal{C} \) and \( \mathcal{E}_C \):

\[
\begin{align*}
\rho \left( \frac{\partial q}{\partial t} \right)_{\text{conv}} &= -\omega^*(-\mathcal{C} + \mathcal{E}_C) + E_p - \frac{\partial \omega^*(q_c - \overline{q})}{\partial p} \\
\rho \left( \frac{\partial q}{\partial t} \right)_{\text{conv}} &= -\omega^* L(\mathcal{C} - \mathcal{E}_C) - LE_p + H - \frac{\partial \omega^*(s_c - \overline{s})}{\partial p} \\
\rho \left( \frac{\partial \theta}{\partial t} \right)_{\text{conv}} &= -\frac{\partial \omega^*(u_c - \overline{u})}{\partial p} \\
\rho \left( \frac{\partial u}{\partial t} \right)_{\text{conv}} &= \cdots
\end{align*}
\]

(5)

The terms \( E_p \) and \( H \), representing evaporation and heat source due to precipitation, remain separate as their magnitude is in no way proportional to the mass flux \( \omega^* \). The scaling between condensation, evaporation, and bulk mass flux is an assumption, reasonable for cumulus and cumulonimbus and more questionable when updrafts are weaker, such as in stratocumulus. This assumption, made in the present prototype, should be reconsidered for further developments. To close this equation set, three components need to be parameterized:

1) A microphysical scheme to produce the cloudy profiles (\( \psi_c \)), condensation (\( \mathcal{C} \)), and cloudy evaporation (\( \mathcal{E}_C \)) rates per unit of vertical length, \( E_p \) and \( H \).

2) A closure to relate the bulk mass flux \( \omega^* \) to the in-cloud vertical velocity \( \omega_c \) through a quantity \( \gamma \) quantifying the area coverage of convection: \( \omega^* = \gamma \omega_c \). \( \gamma \) may vary both in time and vertically.

3) An in-cloud vertical velocity scheme to compute \( \omega_c \).

An example of three such components is given below.

b. Microphysics representation

A prognostic equation is used for water vapor whereas water condensates and precipitation are computed diagnostically.

Microphysics is computed with a one-dimensional model (entraining plume) in which a parcel is raised upward from the lowest model level, computing a dry adiabatic or moist pseudoadiabatic evolution:

\[
\frac{\partial q_{wc}}{\partial z} = \left( \frac{\partial q_{wc}}{\partial z} \right)_{\text{cond}} + \varepsilon (\overline{q}_v - q_{wc}),
\]

(6)

where \( q_{wc} \) is the cloudy water vapor mixing ratio, \( \overline{q}_v \) is the grid-scale water vapor mixing ratio, and \( \varepsilon \) is the entrainment rate:

- \( 6.0 \times 10^{-4} \text{ m}^{-1} \) below 830 hPa,
- \( 1.2 \times 10^{-4} \text{ m}^{-1} \) above 350 hPa,
- a linear function of \( p \) between these two levels. Here

\[
\left( \frac{\partial q_{wc}}{\partial z} \right)_{\text{cond}}
\]
is the condensation rate \((\leq 0)\), determined as the value releasing the water vapor supersaturation with respect to liquid or ice, and

\[
- \left( \frac{\partial q_c}{\partial p} \right)_{\text{cond}}
\]

is the condensation term \((\dot{C})\) from (5). Diagnostic reservoirs of cloud condensates (liquid, ice) are integrated along the parcel ascent: their source is the above condensation; their sink is both the cloudy evaporation and the generation of precipitation, using a crude assumption. For autoconversion all condensates above a given threshold are converted into precipitation (rain, snow). Precipitation falls within a single time step, is assumed to occur partly in the environment (uniform fraction), and is evaporated using an expression derived from Kessler (1969).

c. In-cloud vertical velocity

The vertical kinetic energy is computed as the vertical integral of buoyancy, friction, and nonhydrostatic forces as

\[
w_c \frac{\partial w_c}{\partial z} = B - e w_c^2 - F_{\text{NH}},
\]

which is a simplified version of Eq. (3) of Simpson et al. (1965). The entrainment \(\varepsilon\) is the same as that of thermodynamical variables, for example, (6). The nonhydrostatic effects \(F_{\text{NH}}\) are taken into account following Siebesma et al. (2003) or Bretherton et al. (2004):

\[
w_c \frac{\partial w_c}{\partial z} = aB - b e w_c^2,
\]

where \(a = 1\) and \(b = 2\).

The scheme vertically integrates the net acceleration from Eq. (8). It thus computes a work; typically, this work is first negative—if some convective inhibition (CIN) is to be found—and then might increase above the level of free convection (if such a level exists in the current profile). If the work becomes positive at some level, the scheme is triggered. The maximum value of this work is actually the effective difference between convective available potential energy (CAPE) and CIN, effective meaning here “including the effect of entrainment.” CAPE minus CIN could be positive, even if no condensation has been produced along the ascent: nothing prevents the scheme from dealing with mass flux convective transport within the dry planetary boundary layer (PBL). As mentioned previously, the MTCS equations, coupled with the in-cloud vertical velocity (8) make it possible to compute dry, shallow, and deep convection, using the same parameterization.

However, to keep it simple, the results presented below were obtained with the scheme switched off, when no condensation was detected, and running a separate turbulence scheme. Testing the convective scheme in dry convection mode is a further perspective of the present study.

d. Closure

Closing the equation system (5) means relating the bulk mass flux \(\omega^*\) to the in-cloud vertical velocity \(\omega_c\) through a quantity \(\gamma\) qualifying the area coverage of convection: \(\omega^* = \gamma \omega_c\). For \(\gamma\), the convective scheme prototype uses a constant value \((0.04)\), thus indicating a CAPE-type closure: the vertical velocity \(\omega_c\) has been computed above as the vertical integral of buoyancy so that the maximum value of \(\frac{1}{2}w_c^2\) in the vertical is the effective \((\text{CAPE} \sim \text{CIN})\). More complex closures may be used, for example, as proposed by Robe and Emanuel (1996). However, the present prototype simply aims to show that the MTCS equations can be relevant even with widely used closures.

e. Results

The prototype V1 described above has been tested in a one-dimensional test bed. A variety of contrasting case studies designed either from observations or from more basic process-oriented considerations have been used. This includes tropical cases over the sea, such as observed during GATE, as well as drier cases (EUROCS sensitivity of moist convection to environmental humidity, EUROCS diurnal cycle of deep convection over land).

1) GATE Phase III

We have used grid-scale upper-air datasets analyzed by K. V. Ooyama et al. (1985, personal communication), for the period of GATE Phase III, available at the National Center for Atmospheric Research. A presentation of this data is given in Esbensen et al. (1982). The single-column model (SCM) is initialized with the profile from 0000 UTC 30 August 1974 and then runs a 20-day fully prognostic prediction forced by the analyzed temperature and moisture advections. Figure 2 presents two SCM predictions of precipitation and the reference — observed precipitation data from Hudlow and Patterson (1979). The control run uses the convective scheme in operations in the global Météo-France numerical weather prediction (NWP) Arpege model from Geleyn et al. (1995). This convective scheme (re-
ferred to below as Control) is a modified version of the original Bougeault (1985) scheme, both using a humidity convergence closure. The results obtained with the V1 prototype are quite similar to the Control ones in this particular case. They are also similar to those obtained by Bougeault (1985)—shown in his Fig. 4. Though the V1 scheme differs in many aspects (new grid-scale equations, new microphysics, a CAPE closure instead of a humidity convergence closure, etc.), the MTCS scheme, even with crude microphysics, can reproduce the results obtained by previous schemes. A parameterization using a CAPE closure (V1) can perform similarly to those using convergence closures, even in the GATE case where strong positive dynamical humidity forcings are to be found.

We take further advantage of two distinct and complementary case studies developed within the EUROCS research project.

2) EUROCS SENSITIVITY OF MOIST CONVECTION TO ENVIRONMENTAL HUMIDITY

This case seeks to evaluate the sensitivity of cumulus convection to humidity in the free troposphere; the methodology of Derbyshire et al. (2004) was to compare CSRM and SCM sensitivities to midtropospheric humidity using a test bed relevant to the performance of convection parameterization in GCMs. They concentrated on four quasi-steady regimes, all with the same temperature profiles, but with different humidity profiles. For a detailed description of this study the reader may refer to Derbyshire et al. (2004). Figure 3 shows the sensitivity of four models to midtropospheric humidity: for moist atmospheres (90% relative humidity in the midtroposphere) both CSRMs—used here as a reference—indicate that the total effect of convection over 2 km is a drying. For 70% relative humidity, the total effect becomes neutral, as for 50% and 25% the effect is a moistening.

Despite showing some sensitivity in the midtroposphere, in most of the cases the SCM using the Control convective scheme predicts a drying. This is a common weakness of convective schemes used in this intercomparison exercise; see Derbyshire et al. (2004). The results obtained with the SCM using the V1 scheme are far from perfect, but present some welcome sensitivity, while giving the correct signs and shapes of Q2 for moist and dry regimes. This sounds encouraging for predicting the convective recovery after dry intrusions in the Tropics with a parameterization: this sensitivity is not the result of “fine” tuning but has been seen as resistant to reasonable changes of the tuning parameters. This sensitivity introduces memory: in such a convection scheme, predicted convective towers can penetrate initially dry layers only after the moistening process. This result may be related to the internal consistency of the still simple microphysics included in this prototype, as well as to the MTCS equations in which the tendencies computed by the microphysical part of the parameterization are used, as such, in the grid-scale model equations. Admittedly, this first prototype is still partly static, in the sense that no prognostic equation has been introduced up to now, in addition to the ones from system (2). The following section will present an example of the introduction of a prognostic equation into a MTCS scheme, relating cloud entrainment to precipitation evaporation.
4. Predicting the shallow-to-deep convection transition

a. A fundamental difficulty

As mentioned in the introduction, current GCMs and LAMs have difficulty in capturing the observed phase of the diurnal cycle in convection over land and, more generally, in predicting the shallow-to-deep convection transition (SDCT) over land or sea. In recent years many attempts have been made within parameterizations, modifying triggering conditions or closure assumptions; despite some improvements, the major part of the predicted deep convection phase lead with respect to observations remained. The question remains open as to which processes control the SDCT.

b. A link with entrainment?

Many current convective parameterizations are based on the entraining plume model in which lateral entrainment—like $e$ of Eq. (6)—plays a central role: the higher the entrainment rate, the lower the top of the clouds. Most of the current deep convection schemes use entrainment rates smaller than $4 \times 10^{-4} \text{ m}^{-1}$, as such values are required in the entraining plume model to predict deep penetrative convective clouds. LES studies of shallow cumulus clouds indicate higher values of $e$, however: Siebesma et al. (2003) suggest, for example, values around $10^{-3} \text{ m}^{-1}$. The present dilemma for convective parameterizations is therefore as follows: if entrainment is around $10^{-3} \text{ m}^{-1}$, parameter-
izations successfully predict shallow clouds but fail in predicting deep precipitating clouds. If entrainment is around $10^{-4}$ m$^{-1}$, they successfully predict deep clouds, but with a SDCT that is too short. It transpires that there is a need to estimate variable entrainment rates within convective parameterizations. What is the link between entrainment values and local properties, like temperature or humidity?

c. Entrainment and density currents

Many tests have been performed by authors to relate entrainment to the grid-scale profile of temperature or humidity, using as a validation dataset the reference CSRM data from the Guichard et al. (2004) “diurnal cycle of precipitating convection over land” case. The original idea was to relate entrainment to local relative humidity, bearing in mind that moistening of the mid-atmosphere by shallow and congestus clouds would be required for the transition to deep clouds. However, careful examination of CSRM animations indicated that some deep clouds could develop even in dry environments, if triggered by previously existing density currents: warm and moist air originating from the lower part of the PBL, dynamically uplifted by existing density currents, can reach the level of free convection with almost no entrainment of surrounding air. The stronger the density current uplifting, the closer the lower part of ascent is to a pure adiabatic one.

As density currents are generated by evaporative cooling due to precipitation evaporation, some relationship was therefore also likely between entrainment and past precipitation evaporation. Here is an example of a formulation of such a relation, which should be considered as a first and heuristic step. First, the entrainment rate $\varepsilon$ is related diagnostically to a value $\xi$ giving the probability of undiluted updrafts at the current level:

$$\varepsilon = \frac{[\xi e_n + (1 - \xi) e_s]}{f(p)},$$

where $\xi$ is a prognostic quantity between 0 and 1 (varying in the vertical), $e_n$ and $e_s$ are the minimum and maximum values of entrainment (respectively $3 \times 10^{-4}$ m$^{-1}$ and $1 \times 10^{-3}$ m$^{-1}$), and $f(p)$ is a function of pressure:

- 1.00 below 830 hPa,
- 0.16 above 350 hPa,
- a linear function of $p$ between these two levels.

Second, $\xi$ is given by a prognostic equation, whose source term is precipitation evaporation:

$$\frac{\partial \xi}{\partial t} = \frac{c I_E}{\gamma} - \frac{\xi}{\tau}$$

where $c$ is a tuning constant ($0.1$ kg$^{-1}$ m$^2$), and $I_E$ is the vertical integral from the top of the atmosphere to current level of precipitation evaporation

$$I_E(p) = \int_{p=\infty}^{p} E_{CP} \frac{dp}{g}.$$  

This term represents the source of negative buoyancies and therefore of subsiding currents. In Eq. (10) $\gamma$ is the updraft fraction as defined in the closure part of the scheme ($\gamma = 0.02$ here; the $\gamma$ value was 0.04 in V1), and $\tau$ is a characteristic time (5000 s) for density current dissipation. The convective scheme using the MTCS equations and this entrainment formulation will be referred to below as V2. This scheme differs from V1 only in the formulation of $\varepsilon$ and value of $\gamma$.

TEST ON THE EUROCS “DIURNAL CYCLE OF PRECIPITATING CONVECTION OVER LAND” CASE

This case is interesting for studying the shallow-to-deep convection transition: it has been designed by Guichard et al. (2004) within the EUROCS/GCSS project to analyze the response of CSRM and SCM to the diurnal cycle of boundary layer heating over land in summer. This case study corresponds to the development of dry, then shallow and deep convection over land in summer, mainly forced by surface sensible— and latent—heat fluxes. Below, reference CSRM results obtained on this case by Chaboureau et al. (2004) are compared with three SCM runs: Control, V1, and V2 schemes.

Figure 4 shows $Q_1$ and $Q_2$ simulated by the CSRM, used here as a reference. The top of convective activity extends gradually in the vertical: a dry convection period in the morning, a shallow convection period between 1100 and 1300 local time, and after 1300 h a transition to deep convection. Figure 5 shows $Q_1$ and $Q_2$ simulated by the control SCM (Control scheme); in contrast with the CSRM simulation, this SCM has a phase lead of deep convection with respect to what is actually observed: deep convection starts around 0900 local time, with almost no transition period from shallow to deep. Another weakness is an underestimated moistening of the midtroposphere by convection. These weaknesses are common in present GCM parameterizations, as shown by Guichard et al. (2004). Figure 6 shows $Q_1$ and $Q_2$ simulated by the SCM using the V1 scheme. This scheme significantly improves the prediction over the control scheme, with a larger moistening of the midtroposphere. The predicted diurnal cycle is however still poorly predicted, as deep convection starts around 0900 local time. Figure 7 shows $Q_1$ and $Q_2$ simulated by the SCM using the V2 scheme. Results...
are much closer to what CSRMs indicate in this case: longer period of shallow clouds, larger moistening of the midtroposphere. Not only the time sequence but also the shape of Q1 and Q2 profiles are improved with respect to Control or V1.

The purpose here is not to argue that Eq. (9) should be used as such in a global model. Instead, this encouraging result indicates that convective parameterizations may in the future be able to predict the shallow-to-deep convection transition better by allowing entrainment rates to vary according to the state of convection. The evolution of entrainment may take into account the following multidraft positive feedback: precipitation evaporation generates cooling, a source of density currents that uplift new and less entraining updrafts, a source of enhanced precipitation, and therefore precipitation evaporation.

A recent study, Khairoutdinov and Randall (2006),
using CSRM simulations of convection over Amazonia, shows that the shallow-to-deep transition requires precipitation and the associated cold pools to generate thermals big enough to support the growth of deep clouds. An observational study from Simpson et al. (1980) also advocates the importance of downdrafts in cumulus merging and deepening processes. These two studies and the present article therefore argue that a major mechanism governing the phase lag of deep convection may be that of the above-described multidraft feedback. This positive feedback and the associated time lag can be parameterized.

What is the link between the ability to predict the shallow-to-deep transition and the MTCS equations above? The first answer may be “a loose link,” as any current parameterization that predicts precipitation evaporation can relate this evaporation to updraft entrainment. However, the following consistency is cru-
5. Summary and perspectives

A set of grid-scale equations (called MTCS), for use in subgrid-scale convective parameterizations, is expressed in separate microphysics and transport terms. The equation set can deal with all types of convection, from dry convection to nonprecipitating and precipitating convection. The stationarized cloud mass budget assumption is not required in a MTCS, being therefore more consistent with the introduction of memory through prognostic closures for cloud properties. A convective scheme based on this equation set is easier to validate versus CSRMs or LES, compared to a traditional one: the rhs of the equations of the convective scheme and of CSRMs or LES have the same meaning so that terms can be compared quantitatively without any additional hypotheses. The scheme may also share the same formulation of explicit microphysics with CSRMs or LES.

A first and basic prototype of an MTCS scheme has been successfully tested in a one-dimensional test bed. The new scheme performs comparably to the reference scheme in high relative humidity cases (GATE) and performs better in drier and more difficult cases like the “EUROCS/GCSS sensitivity of convection to environmental humidity.” This sensitivity introduces memory, as such a convection scheme would predict convective towers penetrating initially dry layers, only after the moistening process.

A simple prognostic parameterization of the link between mean cloud entrainment and the history of precipitation evaporation dramatically improves the memory of deep convection, increasing its phase lag with respect to surface forcing; this also improves the ability of the scheme to predict Q1 and Q2 profiles. The present parameterization proposal, even if crude and heuristic, indicates a trend, however: downdrafts play a major role in the shallow-to-deep mechanisms, but they may be more important here through their indirect effect (impact on temperature and humidity due to the new and more protected updrafts forced by the gust fronts generated by these downdrafts) than through their direct effect (impact on temperature and humidity due to the downdraft circulations themselves). In coming years, a more consistent parameterization could be built, based on the same idea: a link between entrainment and past evaporation through, for example, a subgrid convective kinetic energy (CKE) prognostic equation, in which density currents would be the source term, and entrainment a diagnostic function of the resulting CKE.

In the future, results could be improved using more complex microphysics (e.g., prognostic liquid, ice, rain, snow, etc.), getting closer to that of a CSRM, and relaxing the small area assumption. As the MTCS equations can manage all types of convection, in coming years, a possible perspective will be to unify the convection parameterization exercise, using a single equation set at grid-scale, and a single microphysical package. As an example, Gerard (2007) has introduced MTCS equations into a scheme of his own using more complex prognostic microphysics, area fraction, and vertical velocity with encouraging results.

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