Chapter 16

Convective Parameterization for Mesoscale Models: The Kain–Fritsch Scheme

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16.1. Introduction

The Kain–Fritsch (KF) convective parameterization scheme (CPS) is based on the same fundamental closure assumption as the Fritsch–Chappell (FC) (1980) scheme—convective effects are assumed to remove convective available potential energy in a grid element within an advective time period. Its development was motivated by ongoing observational and numerical investigations of mesoscale convective systems that have revealed the potentially significant impact of certain physical processes that were not represented in the FC scheme. For example, in the FC scheme, detrainment from convective clouds to their environment occurs over a limited vertical depth near cloud top. Yet, it has become evident from diagnostic studies (e.g., Leary and Houze 1980; Gamache and Houze 1983) that midlevel detrainment of mass and moisture from deep convective clouds plays an important role in the development of some mesoscale convective systems.

Detrainment effects are more realistically distributed vertically in the KF scheme through the implementation of a new cloud model. This cloud model modulates the two-way exchange of mass between cloud and environment (i.e., entrainment and detrainment) as a function of the buoyancy characteristics of various mixtures of clear and cloudy air. In some environments, the vertical distribution of convective effects changes substantially with the addition of the new cloud model.

The KF scheme is also formulated to assure conservation of mass, thermal energy, total moisture, and momentum. Rigorous conservation of these quantities was not essential for most applications of the FC scheme, since they typically involved relatively short simulations (less than 24 h in duration) with regional-scale models. However, continuing advances in computing power have made it feasible to implement this type of scheme in larger-scale models and over longer time periods. For these and other more general applications, adherence to conservation principles can be critically important.

In our description of the KF scheme in the following subsection, we focus primarily on these two improvements to the original FC scheme. For a more detailed discussion on the KF scheme's closure and operating principles, the reader is referred to chapter 15 on the FC scheme. We follow with some preliminary diagnostic results. Considerations for future additions to the scheme are discussed in the last section.

16.2. Major components of the KF scheme

a. Mathematical formulation of the convective parameterization

Following Anthes (1977), the heating tendency due to subgrid-scale convective processes can be expressed as

$$\left.\frac{\partial\bar{\theta}}{\partial t}\right|_{\mathrm{conv}} = \frac{L}{\pi}\frac{\overline{dq}}{dt} - \frac{\partial(\overline{\omega'\theta'})}{\partial p}, \qquad (16.1)$$

where θ is potential temperature (K), L is the latent heat released during phase change of a unit mass of water substance (J kg^{-1}), π is Exner's function, $c_p(p/p_0)^{R/c_p}$, where c_p is the heat capacity of dry air (J kg^{-1} K^{-1}), p is the pressure (hPa), $p_0 = 1000$ hPa, and R is the gas constant for dry air (J kg^{-1} K^{-1}); dq/dt is the rate of phase change of water substance (kg kg^{-1} s^{-1}), and ω is the vertical pressure velocity [(kg s^{-1})(m s^{-2})(m^{-2})]. The overbar denotes the grid-scale value in a numerical model while the primes indicate the subgrid-scale perturbations. In a manner similar to McBride (1981), the vertical velocity is normalized by the area of a model grid element so that the vertical pressure velocity ω is directly proportional to the convective mass flux. For example, ω_u, representing the updraft mass flux, is given by $\omega_u = -M_u g/A$, where M_u is the updraft mass flux (kg s^{-1}), g is the acceleration due to gravity (m s^{-2}), and A is the horizontal area occupied by a grid element (m^2).

The second term on the rhs of (16.1) can be approximated as the sum of the individual contributions from the updraft mass flux ω_u, the moist downdraft mass flux ω_d, and the compensating mass flux in the environment surrounding the convective drafts $\tilde{\omega}$; that is,

$$\frac{\partial(\overline{\omega'\theta'})}{\partial p} = \frac{\partial[(\omega_u - \bar{\omega})(\theta_u - \bar{\theta}) + (\omega_d - \bar{\omega}) \times (\theta_d - \bar{\theta}) + (\tilde{\omega} - \bar{\omega})(\tilde{\theta} - \bar{\theta})]}{\partial p}, \quad (16.2)$$

where $\omega_d > 0$. By definition, the thermodynamic environment of the updraft and downdraft is given by the resolvable-scale variables, so $\tilde{\theta} = \bar{\theta}$, and the third term on the rhs of (16.2) can be eliminated. Furthermore, if local compensation of convective mass fluxes is assumed—that is, $\bar{\omega} \approx \omega_u + \omega_d + \tilde{\omega} = 0$—(16.2) can be written as

$$\frac{\partial(\overline{\omega'\theta'})}{\partial p} = \frac{\partial[\omega_u\theta_u + \omega_d\theta_d - (\omega_u + \omega_d)\bar{\theta}]}{\partial p}. \quad (16.3)$$

For a given vertical layer in a numerical model, (16.3) can be written in finite-difference form as

$$\frac{\Delta(\overline{\omega'\theta'})}{\Delta p} = \frac{1}{\Delta p}\Bigg\{\overbrace{(\omega_{u2}\theta_{u2} - \omega_{u1}\theta_{u1})}^{\text{A}} + \overbrace{(\omega_{d2}\theta_{d2} - \omega_{d1}\theta_{d1})}^{\text{B}} - [(\omega_{u2} + \omega_{d2})\bar{\theta}_2 - (\omega_{u1} + \omega_{d1})\bar{\theta}_1]\Bigg\}, \quad (16.4)$$

where the subscript 2 denotes the top of a given model layer and the subscript 1 denotes the bottom.

Expressions for θ_{u2} and θ_{d1} can be written as functions of θ_{u1} and θ_{d2}, respectively. For example, in convective updrafts, as parcels rise from the bottom to the top of a model layer, their potential temperature changes as a function of mixing with the environment and latent heat release/absorption. Specifically, the term A in (16.3) can be written as

$$\omega_{u2}\theta_{u2} = \omega_{u1}\theta_{u1} - \epsilon_u\bar{\theta}_m + \delta_u\theta_{um} - \frac{L}{\pi}\omega_{u2}\Delta q_u, \quad (16.5)$$

where ϵ_u is the rate of entrainment of environmental mass into the updraft, $\bar{\theta}_m$ is the mean environmental potential temperature in the layer, δ_u is the rate of detrainment of updraft mass into the environment, θ_{um} is the mean updraft potential temperature in the layer, and Δq_u is the total mass of water substance, per unit mass of air, that changes phase (to a higher energy state, i.e., $\Delta q_u > 0$ for evaporation, melting, and sublimation) in updraft parcels as they rise through the layer. Entrainment and detrainment rates, ϵ and δ, respectively, are expressed in the same units as ω and are always positive. Similarly, the term B can be written in an analogous form for convective downdrafts as

$$\omega_{d1}\theta_{d1} = \omega_{d2}\theta_{d2} + \epsilon_d\bar{\theta}_m - \delta_d\theta_{dm} - \frac{L}{\pi}\omega_{d1}\Delta q_d. \quad (16.6)$$

Substitution of (16.5) and (16.6) into (16.4) yields

$$\frac{\Delta(\overline{\omega'\theta'})}{\Delta p} = \frac{1}{\Delta p}[(\omega_{u2} + \omega_{d2})\bar{\theta}_2 - (\omega_{u1} + \omega_{d1})\bar{\theta}_1 + (\epsilon_u + \epsilon_d)\bar{\theta}_m - \delta_u\theta_{um} - \delta_d\theta_{dm} - \frac{L}{\pi}(\omega_{u2}\delta q_u - \omega_{d1}\delta q_d)]. \quad (16.7)$$

Upon substitution of (16.7) into (16.1), the latent heating terms can be eliminated to yield

$$\left.\frac{\Delta\bar{\theta}}{\Delta t}\right|_{\text{conv}} = \frac{1}{\Delta p}[(\omega_{u2} + \omega_{d2})\bar{\theta}_2 - (\omega_{u1} + \omega_{d1})\bar{\theta}_1 + (\epsilon_u + \epsilon_d)\bar{\theta}_m - \delta_u\theta_{um} - \delta_d\theta_{dm}]. \quad (16.8)$$

From this expression, it can be seen that convective heating in a model layer is given by the sum of the fluxes of environmental potential temperature through the top and bottom of the layer (recall that $\tilde{\omega} \approx \omega_u + \omega_d$), minus the flux into convective drafts, plus the flux from the convective drafts into the environment, where the net mass flux into the layer is zero. In terms of total mass in a layer, any mass surplus or deficit created by entrainment into and/or detrainment out of convective drafts is exactly balanced by compensating fluxes through the top and bottom of the layer. In this way, the resolvable-scale grid in a numerical model "feels" updrafts and downdrafts within a grid element only indirectly. In contrast to FC, the grid-scale temperature in a layer is not in any way a function of the updraft or downdraft temperature in that layer unless there is active detrainment in the layer.

Following the same logic, one can arrive at an expression for the net tendency of specific humidity q_v due to subgrid-scale convection; that is,

$$\left.\frac{\Delta\bar{q}_v}{\Delta t}\right|_{\text{conv}} = \frac{1}{\Delta p}[(\omega_{u2} + \omega_{d2})\bar{q}_{v2} - (\omega_{u1} + \omega_{d1})\bar{q}_{v1} + (\epsilon_u + \epsilon_d)\bar{q}_{vm} - \delta_u q_{vum} - \delta_d q_{vdm}]. \quad (16.9)$$

In addition, liquid water detrainment from convective clouds supplies moisture to the resolvable scale. This process can be represented as a source of cloud water q_c, if used in a model with explicit prediction of cloud water,

$$\left.\frac{\Delta\bar{q}_c}{\Delta t}\right|_{\text{conv}} = -\frac{\delta_u q_{lum}}{\Delta p}, \quad (16.10)$$

where q_{lum} is the mean updraft liquid water mixing ratio in a layer. Alternatively, if cloud water is not an explicitly predicted variable on the resolvable scale, it is assumed that cloud water evaporates (sublimates) in the cloud environment, necessitating an additional source term in (16.9) and an evaporative (sublimative) cooling term in (16.8).

Finally, as in FC, momentum transport in convective clouds is crudely simulated by assuming conservation of momentum in convective drafts. This yields the corresponding momentum tendency equations

$$\left.\frac{\Delta\bar{u}}{\Delta t}\right|_{\text{conv}} = \frac{1}{\Delta p}[(\omega_{u2}+\omega_{d2})\bar{u}_2 - (\omega_{u1}+\omega_{d1})\bar{u}_1 + (\epsilon_u+\epsilon_d)\bar{u}_m - \delta_u u_{um} - \delta_d u_{dm}] \quad (16.11)$$

and

$$\left.\frac{\Delta\bar{v}}{\Delta t}\right|_{\text{conv}} = \frac{1}{\Delta p}[(\omega_{u2}+\omega_{d2})\bar{v}_2 - (\omega_{u1}+\omega_{d1})\bar{v}_1 + (\epsilon_u+\epsilon_d)\bar{v}_m - \delta_u v_{um} - \delta_d v_{dm}]. \quad (16.12)$$

Equations (16.8) and (16.9) are essentially equivalent to the flux form of the apparent heat source and moisture sink equations derived by Ooyama (1971), Yanai et al. (1973), Arakawa and Schubert (1974), and others, although they are derived under a slightly different set of assumptions. Use of the flux form is essential for conservation of advected quantities. Conservation of moisture and thermal energy also relies on an accurate representation of latent heating effects in convective updrafts and downdrafts, the formulations of which are described in the next section.

b. *An entraining–detraining plume model of convective updrafts*

Convective updrafts (and downdrafts) have been traditionally represented in CPSs by Lagrangian one-dimensional entraining plume (ODEP) models (e.g., Arakawa and Schubert 1974; Kreitzberg and Perkey 1976; Tiedtke 1989). These models are desirable because of their computational simplicity, but they are quite inflexible with regard to interactions between clouds and their environment. In particular, both entrainment and detrainment rates must be prespecified in an ODEP, which unrealistically restricts the vertical distributions of convective effects. Most significantly, the vertical heating profile and the vertical distribution of moisture detrainment are severely constrained by the prespecified parameters. Since numerous studies have shown that the impact of moist convection on larger-scale processes is extremely sensitive to these vertical distributions (e.g., Gyakum 1983; Hack and Schubert 1986; Kuo and Reed 1988), an updraft model that is responsive to variations in convective environments is desirable.

A new entraining–detraining plume model (ODEDP) that allows for more realistic cloud–environment interactions and thermodynamic processes, while introducing minimal additional computational requirements, is introduced with the KF scheme. The unique feature of the ODEDP is the mixing scheme that it uses to modulate updraft entrainment and detrainment rates. The scheme computes the buoyancy variations induced by turbulent mixing, in various proportions, between clear and cloudy air. It allows those mixtures that remain positively buoyant in each model layer to continue to rise with the updraft, while the mixtures that lose their positive buoyancy, through evaporative cooling effects, detrain into the environment. As discussed in detail in KF (1990), this scheme provides a realistic element of cloud–environment interaction so that vertical distributions of environmental entrainment, updraft detrainment, and net updraft mass flux can vary considerably as a function of the cloud-scale environment.

The new cloud model utilizes a more detailed representation of cloud microphysical processes than the original FC cloud model. Updraft thermodynamic processes are based on conservation of equivalent potential temperature θ_e (using Bolton's 1980 formula) and total water substance. Conversion of condensate to precipitation is simulated using a Kessler-type (Kessler 1969) autoconversion equation, as in Ogura and Cho (1973). Ice-phase thermodynamics are included, with a gradual transition between the liquid and ice phases occurring within a specified temperature interval. The transition to ice-phase thermodynamics requires an adjustment of θ_e values, as discussed in KF.

c. *Convective downdrafts*

The parameterization of convective downdrafts in the KF CPS contains a number of procedural differences from the downdraft formulation in FC. Most of these differences were implemented to assure conservation of all variables. Conceptually, however, the algorithms are very similar in KF and FC. Based on the empirical evidence of Foster (1958), downdrafts are initiated at the highest level below about 500 hPa at which a mixture containing equal parts of updraft and environmental air, when brought to saturation, becomes negatively buoyant with respect to the environment. Like the updraft, downdraft thermodynamics are based on conservation of θ_e (with an adjustment for melting effects), and evaporation of condensate is assumed to maintain a specified value of relative humidity at each level, typically 100% in the cloud layer and 90% below. Downdraft vertical velocity is computed using the buoyancy equation, and the downdraft is allowed to penetrate downward to the lowest layer where integrated buoyancy effects allow negative vertical velocity to be maintained.

The downdraft mass flux is related to the updraft mass flux through a precipitation efficiency relationship. The precipitation efficiency is determined by equally weighting estimates based on the vertical shear of the horizontal wind (as in FC) and cloud-base height (Fujita 1959; Zhang and Fritsch 1986). This efficiency estimate is applied to the total rate of precipitation generation in the updraft. The downdraft mass flux then corresponds to the maximum transport of mass that can be maintained at the specified relative humidity and over the estimated depth for the given availability of liquid water.

d. Convective environment

The KF scheme accommodates the influence of convective updrafts and downdrafts on their environment in a considerably different manner than the FC scheme. Detrainment of updraft temperature, moisture, and momentum are all calculated explicitly, as included in Eqs. (16.8)–(16.12). In the original FC scheme, the effects of updraft overshooting and detrainment on the temperature field are inferred from consideration of energy conservation above the equilibrium temperature level; the effects of updraft water vapor and momentum detrainment are not included. The total tendencies expressed by Eqs. (16.8)–(16.12) are held constant throughout the convective time period, rather than integrating forward in time as is done in the FC scheme, and there is no explicit area averaging as in FC.

16.3. Preliminary results

A primary motivation behind the development of the new cloud model and, to a lesser degree, the other modifications to the FC scheme was to expand the design of the original FC scheme to encompass a broader spectrum of convective environments. The efficacy of the FC scheme has been demonstrated in numerical simulations of continental mesoscale convective systems in the midlatitudes (e.g., Zhang and Fritsch 1986, 1988b; Zhang et al. 1989), but it has not been well tested in, for example, maritime tropical environments. However, preliminary results of diagnostic tests of the KF scheme in tropical environments are very encouraging. For example, consider the heating profiles diagnosed for the GATE [GARP (Global Atmospheric Research Program) Atlantic Tropical Experiment] environment by Frank and McBride (1989). These profiles are particularly well suited for comparison with heating profiles generated by the KF scheme because they are computed as a function of the stage of development of mesoscale convective systems (MCSs). Since the KF scheme parameterizes only the effects of deep convection (with the assumption that mesoscale stratiform components will be explicitly resolved), Frank and McBride's relatively high temporal resolution allows us to focus on the initial stages of MCSs, which were observed to be dominated by deep convection in the GATE environment (Houze and Betts 1981).

Figure 16.1a shows a composite of pre-MCS soundings for the GATE sounding array. Figure 16.1b shows the corresponding diagnosed apparent heat source for the initial stage (first 3 h) of MCSs in this environment. Figure 16.2a shows two heating profiles generated by the KF scheme with this input sounding. The dashed profile is derived by turning off lateral detrainment (below cloud top) in the new cloud model so that it behaves like a simple entraining plume model. The solid profile is derived by allowing the new cloud model to execute normally. Clearly, the new cloud model has a substantial, and favorable, impact on the vertical heating profile generated by the KF scheme, with the parameterized vertical distribution matching the diagnosed distribution remarkably well. The magnitudes of the parameterized and diagnosed values differ considerably, but this is likely to be due to the disparity in

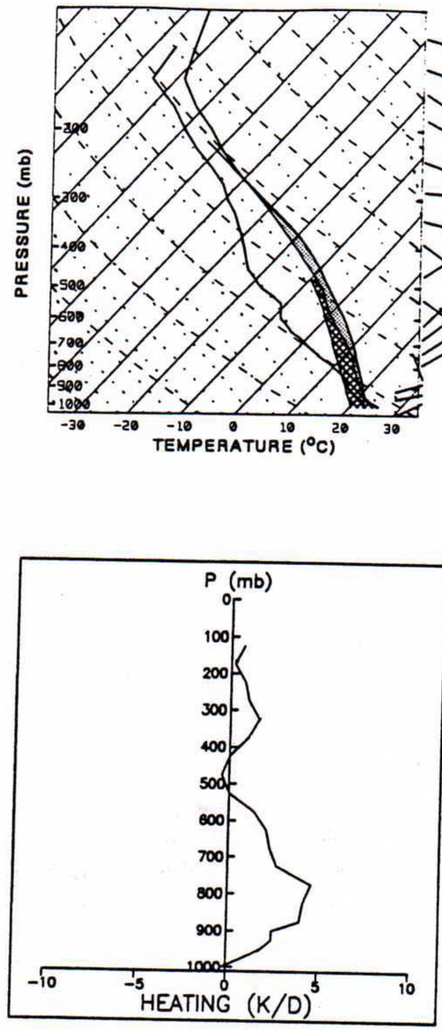

FIG. 16.1. Tropical (GATE composite) environmental sounding showing the positive area given by the new cloud model (stippled) and the downdraft negative area given by the downdraft plume model in the KF scheme (cross-hatched) (a) and diagnosed vertical distributions of diabatic heating from Frank and McBride (1989) for the initial stages of mesoscale convective systems in this environment (b).

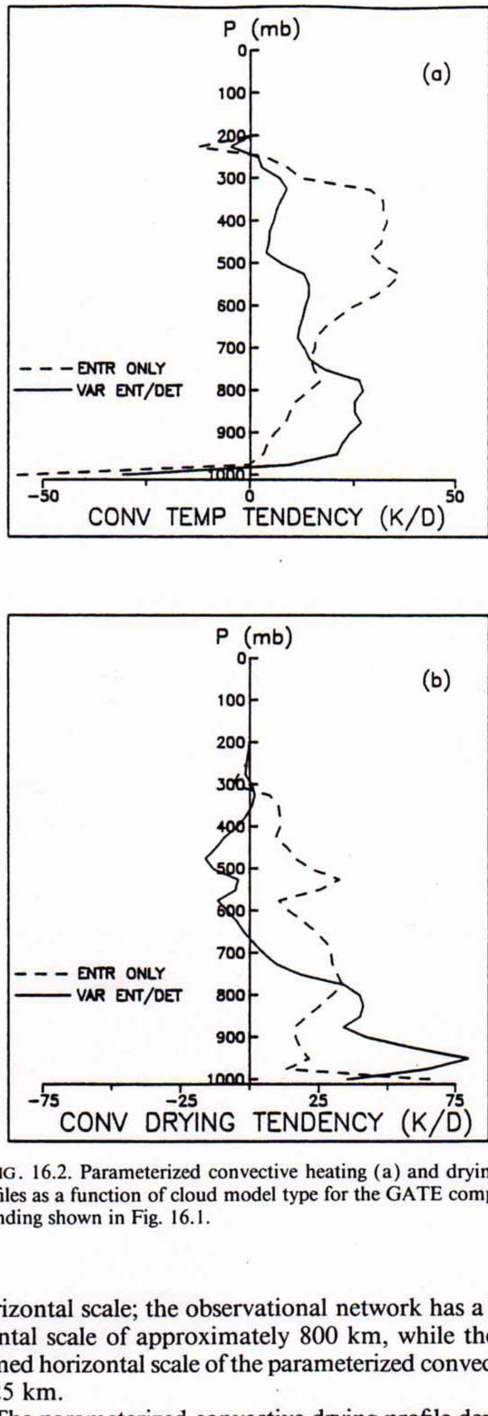

FIG. 16.2. Parameterized convective heating (a) and drying (b) profiles as a function of cloud model type for the GATE composite sounding shown in Fig. 16.1.

horizontal scale; the observational network has a horizontal scale of approximately 800 km, while the assumed horizontal scale of the parameterized convection is 25 km.

The parameterized convective drying profile derived using the new cloud model (Fig. 16.2b) is also consistent with the diagnosed distribution in this environment. The diagnosed drying maximizes at a lower level than the heating and becomes negative (moistening) in the mid- and upper troposphere during the early stages of the GATE systems (Frank, personal communication). The change in sign of the parameterized tendency is largely due to the detrainment of cloud hydrometeors, which is included as a moistening effect in the profiles shown Fig. 16.2b. The ability of the KF scheme to generate realistically this mid- and upper-tropospheric moisture source for resolvable-scale circulations is likely to be an important ingredient in the successful simulation of MCSs (Molinari and Dudek 1992). Numerous studies have indicated that deep convective clouds supply a significant fraction of the moisture that eventually falls as precipitation in the stratiform regions of MCSs (e.g., Leary and Houze 1980).

The KF scheme has been tested in a diagnostic mode in various other types of convective environments with equally encouraging results (KF 1990). A more thorough assessment of its performance is being carried out through testing in three-dimensional prognostic simulations (e.g., Kain and Fritsch 1992) and forecasts [in the "semioperational" version of the Pennsylvania State University (Penn State)–National Center for Atmospheric Research (NCAR) Mesoscale Model (Warner and Seaman 1990)] in various environments. In general, the preliminary results substantiate the basic hypothesis of FC (and Kreitzberg and Perkey 1976): a realistic parameterization of the intensity and vertical distribution of the effects of deep convection on the mesoscale can be achieved without regard to instantaneous larger-scale tendencies.

16.4. Considerations for further modifications

The continued rapid development of numerical models and methods must be accompanied by corresponding development of physical parameterizations if improvements in numerical weather prediction are to be expected. Listed below are two areas of change that are likely to be addressed in the KF scheme in the near future.

a. Feedback to the resolvable scale through convective mass sources and sinks

Derivation of Eqs. (16.8), (16.9), (16.11), and (16.12) requires an assumption that mass tends to be conserved in every model layer by vertical motions in the convective environment that exactly compensate for the vertical mass fluxes in convective drafts. The quantitative validity of this assumption becomes questionable as resolvable-scale grid lengths come down below the Rossby radius of deformation and approach the scale of individual convective clouds.

In general, a more realistic approach may be to solve for the compensating environmental motions on the resolvable scale by including convective mass source and sink terms in a resolvable-scale continuity equation. In hydrostatic models, however, this approach may still have serious drawbacks. For example, one could force compensating subsidence to occur on the resolvable-scale grid. Mathematically, this would be identical to the current approach for the first time step in a convective time period. In subsequent time steps, however, convectively induced subsidence would be vertically advecting quantities that are evolving with time at any given point. This would seem to be more realistic than the current approach, which feeds back the same values for convective tendencies at a given point at each time step during the convective time period. Yet, this approach would still force all of the compensation to occur locally, and in the vertical only.

Alternatively, one could introduce subgrid-scale mass sources and sinks in terms of horizontal pressure gradient forces. This could be implemented by adjusting the geopotential or pressure at each level and each time step to reflect the unresolvable vertical transports of mass into or out of a layer. This approach may be difficult to implement within the framework of current numerical models. Furthermore, it forces all of the compensating motions to occur through horizontal wind fields. Subsidence warming would presumably occur some distance away from the active convection, in contrast to both theory and observations (e.g., Lilly 1960; Fritsch 1975).

The mass source–sink type of feedback may be practicable only in nonhydrostatic models. Within the nonhydrostatic set of governing equations, mass sources and sinks can simultaneously induce responses in both the horizontal and vertical wind fields through the perturbation pressure field (Golding 1990). Current plans are to incorporate the KF scheme with this type of feedback in the nonhydrostatic version of the Penn State–NCAR model (Dudhia 1993).

b. Convective momentum transports and detrainment induced by horizontal momentum

Numerous studies have indicated that conservation of momentum in convective updrafts and downdrafts may be a poor assumption under some conditions (LeMone et al. 1984; Matejka and LeMone 1990b; Gallus and Johnson 1992). In particular, it appears that updraft and downdraft parcels can undergo substantial horizontal accelerations in response to local pressure gradient forces. A more sophisticated parameterization of convective momentum transport, such as that proposed by Zhang and Cho (1991), may be appropriate for the KF scheme.

A more realistic momentum parameterization may also allow for the implementation of a mass detrainment mechanism based on the differences in horizontal momentum between a cloud and its environment. Clearly, when convective updrafts rise through cloudy environments, some mechanism other than evaporatively induced negative buoyancy must be operative in the detrainment of updraft mass into the environment.

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