Comments on "An Analysis of Diagnostic Cloud Mass Flux Models"

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Mc Bride (1981) recently compared and contrasted features of various diagnostic models that are used to determine the collective properties of ensembles of cumulus clouds. A remark is made in the closing section of his paper discussing what he terms are "inconsistencies" that arise in application of certain diagnostic procedures. In short, he argues that the feeding of convective mass fluxes derived from the moist static energy (h) budget into the component equations for dry static energy s and specific humidity q (written in terms of cloud-modeled convective mass fluxes for the cloud layer) will not necessarily yield, say from the q equation, precipitation estimates that are in agreement with those obtained from the moisture (q) budget vertically integrated through the entire troposphere. Mc Bride uses the procedure of Johnson (1976) to illustrate his point.

While I technically agree with Mc Bride on this matter, his discussion and use of the word inconsistency could be construed by many readers to imply that the diagnostic models of Johnson (1976) and others that are similar are basically inconsistent. Despite their limitations, this is not the case and because diagnostic models have received widespread use in recent years, this issue is worthy of clarification.

Using Mc Brides' notation, expressions for the "apparent heat source" Q_1, "apparent moisture sink" Q_2, and "apparent moist static energy source" $Q_1 - Q_2 - Q_R$ are

$$Q_1 \equiv \frac{\partial \bar{s}}{\partial t} + \bar{\mathbf{v}}\cdot\nabla\bar{s} + \bar{\omega}\frac{\partial \bar{s}}{\partial p} = -\frac{\partial \overline{s'\omega'}}{\partial p} + L(c-e) + Q_R, \quad (1)$$

$$Q_2 \equiv -L\left(\frac{\partial \bar{q}}{\partial t} + \bar{\mathbf{v}}\cdot\nabla\bar{q} + \bar{\omega}\frac{\partial \bar{q}}{\partial p}\right) = L\frac{\partial \overline{q'\omega'}}{\partial p} + L(c-e), \quad (2)$$

$$Q_1 - Q_2 - Q_R = \frac{\partial \bar{h}}{\partial t} + \bar{\mathbf{v}}\cdot\nabla\bar{h} + \bar{\omega}\frac{\partial \bar{h}}{\partial p} = -\frac{\partial \overline{h'\omega'}}{\partial p}, \quad (3)$$

where Q_R is the net radiative heating rate, c is condensation and e evaporation. Definitions of other symbols used in these comments are found in the two papers cited above. Integrating (2) from the tropopause p_T to the surface p_s yields

$$P_0 = g^{-1}\int_{p_T}^{p_s} \frac{Q_2}{L}dp + E_0, \quad (4)$$

where P_0 is precipitation at the ground and E_0 surface evaporation. Eq. (4) is equivalent to Mc Bride's Eq. (46), but it should be noted that the limits of integration in his expression should be reversed. Large-scale observations of Q_2 and surface evaporation measurements can be used with (4) to compute P_0.

Alternatively, Eq. (2) may be integrated to cloud base p_B to give

$$P_B = g^{-1}\int_{p_T}^{p_B}(c-e)dp = g^{-1}\int_{p_T}^{p_B}\frac{Q_2}{L}dp - g^{-1}(\overline{q'\omega'})_{p_B}, \quad (5)$$

where P_B is precipitation at cloud base. Eq. (5) may also be used to determine precipitation at the ground P_0 if some estimate is made of precipitation evaporation in the subcloud layer. In principle, P_0 determined from (4) and (5) should agree, as Mc Bride points out. However, the last term in (5), which represents the subgrid or cumulus water vapor flux at cloud base, can take on a variety of forms and values depending on the cloud models used. If more realistic convective elements are added to a simple cumulus updraft model [e.g., cumulus downdrafts of various sizes (Johnson, 1976); bulk cumulus downdraft (Nitta, 1977); cloud life-cycle effects (Cho, 1977); mesoscale updrafts and downdrafts (Houze, *et al.*, 1980)] then additional degrees of freedom are added which require specification of additional parameters, constraints or assumptions to close the problem. This statement is true regardless of whether the single budget equation for h is used (Johnson, 1976; Houze *et al.*, 1980) or the individual budget equations for s and q are used (Nitta, 1977; Cho, 1977) to determine cloud mass fluxes.

The cloud model in Johnson (1976) consists of

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entraining plumes for cumulus updrafts and downdrafts. He defines $\epsilon(\lambda) \equiv m_0(\lambda)/m_B(\lambda)$, where λ is entrainment rate, $m_B(\lambda)$ the updraft mass flux per unit λ at cloud base, and $m_0(\lambda)$ the downdraft mass flux per unit λ at the downdraft originating level, and specifies its value based on (i) calibration of model-computed precipitation with observed and (ii) a water vapor budget for the subcloud layer. In procedure (i), the only one commented on by Mc Bride, $m_B(\lambda)$ is determined from an integral equation for the moist static energy h [e.g., Eq. (35) of Mc Bride], with (5) applied as an integral constraint to determine an optimum value of ϵ. The physical basis for (i) is related to the water budgets of the cloud systems. As noted in Johnson (1976, Fig. 7), a diagnostic model having only cumulus updrafts (modeled as entraining plumes) yields precipitation in excess of that observed. In reality, much of the water condensed in updrafts is re-evaporated in cumulus downdrafts, the intensity of which is measured by ϵ. Therefore, ϵ is used here to determine the amount of evaporation in downdrafts required to bring model-computed and observed precipitation into agreement. The fact that both will not agree for any ϵ is evident from the consideration that solution of (5) requires $m_B(\lambda)$ and $m_0(\lambda)$ in the eddy flux terms. Since $m_B(\lambda)$ is obtained by solving the h budget equations, it depends on Q_1, Q_2, and Q_R. Thus, P_0 obtained from (5) depends on Q_1, Q_2, and Q_R whereas P_0 from (4) depends only on Q_2. The two solutions will certainly not agree for arbitrary ϵ. Eqs. (4) and (5) can be constrained to yield the same P_0 for a constant ϵ (Johnson, 1976) or for an ϵ with specified functional form (Johnson, 1980). These procedures have also been recently discussed by Johnson (1980; see section 7). The closure statement of Johnson (1976) itself, *viz.*, $\epsilon(\lambda) = m_0(\lambda)/m_B(\lambda)$, has been recently put on a much firmer physical basis by Houze *et al.* (1980), who express $\epsilon(\lambda)$ as a product of terms representing physical processes relating to the cloud water budget and precipitation efficiency.

In essence, then, the assertion is made in (i) that the precipitation at the ground determined from (5), i.e., P_B − (precipitation evaporated in subcloud layer), should agree with the observed precipitation. Likewise P_0 determined from (4), within the accuracy of the data, should agree with observed precipitation. The fact that (5) can give estimates of precipitation that differ from those given by (4) probably should not be interpreted as "the equations have a degree of freedom they should not have", but rather as an indication that the application of cloud models to represent subgrid convective fluxes introduces additional degrees of freedom, requiring, if unique solutions are to be had, 1) the assignment of specific parameters or coefficients associated with these models or 2) additional assumptions. For example, in Nitta's (1977) approach, a parameterization of the rain formation process is introduced and a cloud droplet-to-liquid water autoconversion coefficient is specified. However, the assignment of parameters in models such as these, although permitting solutions to be obtained, does not guarantee that they will be physically realistic. It is therefore important to apply, whenever possible, additional physical constraints to narrow the ranges of the parameters in the models. The methodology of Johnson (1976) involving both procedures (i) and (ii) is an attempt to remove the arbitrariness associated with the assignment of specific parameters in that 1976 model.

In summary, these comments address statements made by Mc Bride (1981) that suggest inconsistencies can arise associated with procedures used to diagnose convective mass fluxes from large-scale observations. It is shown here that for the procedure used by Johnson (1976) there are no inconsistencies in the basic equations [Eqs. (4) and (5)]. Use of cloud models to represent eddy flux terms, however, introduces arbitrariness which may lead to physically unrealistic solutions to the basic equations. Calibrating model-computed precipitation against observed precipitation is a method for removing arbitrariness in the assignment of the cloud model parameter involved in Johnson's treatment of the equations. As the cloud models used to represent terms in the basic equations become more realistic, e.g., by inclusion of mesoscale updrafts and downdrafts (Houze *et al.*, 1980), the number of parameters or coefficients that must be assigned may become sufficiently great that they cannot be determined by integral or other constraints, but rather realistic ranges of the parameters have to be defined (e.g., Houze and Cheng, 1981).

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