Comments on "Steady-State One-Dimensional Models of Cumulus Convection"[1]

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1. Introduction

In a recent article, Warner (1970) reviewed current steady-state one-dimensional cumulus models and found them lacking a sound physical basis. Part of the foundation for that conclusion was the model's inability to simultaneously predict liquid water content and cloud depth. A corollary conclusion of the discussion was that any prediction success enjoyed by steady-state one-dimensional cumulus models was due to empirical adjustments which might not be valid under conditions other than those tested.

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The purpose of this note is twofold: 1) to clarify some general misconceptions concerning steady-state one-dimensional models, and 2) to correct some definite errors in Warner's article.

2. Objectives and application of steady-state one-dimensional cumulus models

The primary objective of the Pennsylvania State University (PSU) cumulus model as described in Weinstein and Davis (1968) was to provide a tool that was 1) sufficiently realistic to predict the gross aspects, as opposed to the intricate details, of convection in isolated cumuli, and 2) simple enough to run rapidly on small computers.

This objective restricts the application of the model to situations where the predictions of the general features of convective activity (i.e., cloud top height, precipitation, maximum vertical velocity, and/or buoyancy) are desired. These general features do not include the details of the internal cloud structure and the model should not be held accountable for these predictions.

Some appropriate applications of models of this type that have been used are as follows:

1) In sensitivity analyses "...to isolate the role played by each complicated phenomenon [in cumulus clouds], [in order to] decide which should be modeled in detail and to determine the necessary field data needed for comparative studies."[2]
2) In conjunction with weather modification field projects "...as a help in selecting test clouds for which the dynamics effect [of seeding] is expected to be large.", and "...to help with the evaluation results."[3]
3) In ice-phase seedability potential studies "...to learn when, where, under what conditions, and to how great an extent this form of weather modification can be effectively used."[4]

One of the results of the sensitivity analysis studies carried out with the PSU model was the insufficiency of the lateral entrainment assumption. Some modifications along the lines proposed and tried by Warner were suggested in the Weinstein-Davis publication. The entrainment assumption has been most consistently pointed to as a weak point in steady-state one-dimensional models. It is admittedly the weakest point and is definitely subject to change when a better mixing assumption is proposed, shown to be more accurate, and shown to be practical for fast computer application.

Other approaches to mixing, such as vertical entrainment, have been suggested as possible improvements on the lateral entrainment concept. None of these approaches, however, have ever been shown to be more accurate than lateral entrainment nor have they ever been shown to be practical in a small, fast computing model. When alternative mixing hypotheses are shown to be appropriate for these models, the hypotheses will be gratefully applied. Until that time, the lateral entrainment hypothesis is the best available and must be used.

The most important *gross aspect* predictions needed from the cumulus models in support of weather modification activities are cloud top height and precipitation from seeded and natural clouds. In fact, the important prediction is that involving the relative differences *between* seeded and natural cumuli, not necessarily the absolute values. The cloud-top height prediction skill has been shown in several different geographical areas ranging from Arizona (Weinstein and MacCready, 1969), to the Caribbean area (Sax, 1969), to the central United States and Canada (Marwitz *et al.*, 1970), and even to the Australian results of E. J. Smith that Warner presented. Some empirical adjustments may have been required to obtain some of the above-stated results. In the case with which the author has most familiarity, however, (Sax, 1969), a totally unadjusted version of the PSU model, using $\mu=0.2$ and normal values for the cloud microphysics parameters, and applied to a geographical area for which it had not been designed, gave almost as good cloud-top height predictions as the model designed for that area. The correlation between observed and predicted cloud tops was 0.92 and 0.98 for the PSU and EMB[2] (Simpson *et al.*, 1965) models, respectively.

The only quoted precipitation verification using steady-state one-dimensional models is the good skill described in the Weinstein and MacCready article and the results given by Warner attributed to E. J. Smith. No further comments can be made on the Smith results since no indication is given how the precipitation was measured, nor if the potential pitfalls of the precipitation prediction that were described by Weinstein and MacCready (1969) were avoided.

3. Predictions from the model and comparison with observation

The above discussion notwithstanding, since the PSU model output does include profiles of the internal cloud parameters, these profiles will inevitably be compared with observations. Warner made such a comparison and found that the model was unable to simultaneously predict both cloud top height and liquid water content accurately.

The most serious error of Warner's article is in the choice of data used for the prediction verification test. The model calculations are made on a closed parcel into which there is no addition or removal of water or air (except by entrainment). The only part of the cloud that can be simulated by such a closed parcel is the leading parcels of a growing cloud. It turns out that the height attained by these leading parcels is generally

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[2] Weinstein and Davis (1968), p. 1.

[3] Weinstein and MacCready (1969), p. 936.

[4] Todd *et al.* (1968), p. 280.

[2] Experimental Meteorology Branch.

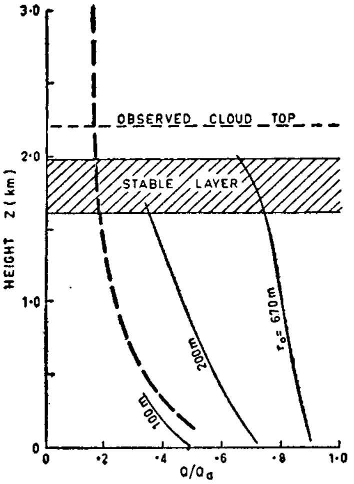

FIG. 1. Predicted Q/Q_a ratios as a function for height for the model of Weinstein and Davis in which the mixing rate for water is constant with height but that for heat and momentum changes as the central plume radius changes. The initial updraft was taken as 1 m sec^{-1} and the initial temperature excess as zero (after Warner, 1970).

the maximum cloud top height ever attained by the cloud, so cloud top height observations are valid for comparison. The liquid water content profile, however, is constantly changing, and thus the only valid data for comparison of this parameter are those taken in the leading parcels of the cloud. The data presented by Warner were not taken in these leading parcels.

Fig. 1 is used in support of this contention. Notice that all of the values of observed liquid water content are less than the adiabatic value. Since the adiabatic value is the limiting liquid water content, what happened to the liquid water between Warner's observed curve and the $Q/Q_a = 1$ line? There are three possible explanations for the disappearance of the water, i.e., 1) it was never condensed in the first place, 2) it fell out of the cloud as rain, or 3) it was lost through evaporation.

The first explanation is rejected since the primary source of energy available to cause the cloud to grow in the first place is the energy derived from latent heat of condensation.

Warner rejected the second explanation since the observations were made in non-raining clouds. This rejection might be premature since even in non-raining clouds it is possible for water to be redistributed in the vertical. (Simpson discusses this point in more detail in a note in the April 1971 issue of this journal.)

The only remaining viable explanation for the disappearance of the water is evaporation. The model presently simulates this evaporation in the leading cloud parcels. It can be seen in Fig. 1 that this evaporation in a 670 m radius cloud is insufficient to bring the observed and calculated liquid water content profiles into agreement. If the liquid water content between the two curves (~1.5 gm m^{-3}) is forced to be evaporated in the model calculations, the parcel's positive buoyancy is completely destroyed. In fact, the cloud becomes strongly negatively buoyant. If the observations and calculations must both represent the leading parcels, these leading parcels would never accelerate and the cloud would never form. In principle, this is what happens in the calculations of the small clouds shown in Fig. 1.

If the liquid water content observations were made later in the cloud's lifetime rather than in these leading parcels, the evaporation and negative buoyancy could have existed. Warner (1969) states that the liquid water content observations were taken in clouds "...which appeared to be growing...." No mention is made of temperature observations. From the quote, one would assume that the clouds were growing and thus not negatively buoyant. This could be misleading however, as it has been observed by Weickmann *et al.* (1970) in "...actively growing cloud with well-defined and bulging cumulus contours..." that such clouds are frequently, if not always, negatively buoyant through much of their lifetimes.

It is seen that there is a plausible explanation for the discrepancy between the liquid water observations and calculations other than the hypothesis that the model is unrealistic. The alternative explanation is that the observations were made at some time or place in the cloud other than where the model simulation holds. Under these conditions, the calculations and observations should not be expected to agree.

4. Mixing rates for heat and moisture

The final point that must be raised concerns an allegation made by Warner that the PSU model exhibits "...peculiarities in the use of different mixing rates for heat and moisture (only fully apparent in the computer program listed in the 1968 paper) which are hard to reconcile on physical grounds." The statement is false in its parenthetical remark and questionable in its

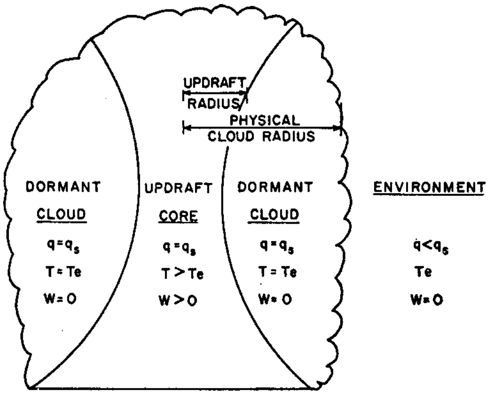

FIG. 2. Schematic representation of cloud and environmental parameters (q, mixing ratio; T, temperature; W, vertical velocity; qs, saturated mixing ratio; Te, environmental temperature) in a typical cumulus cloud (after Weinstein and Davis, 1968).

main point. The justification for the use of the different mixing rates is clearly given on pp. 13 and 14 of the Weinstein and Davis (1968) publication. Fig. 2, reproduced from that publication, helps to explain the physical basis for the different mixing rates. In a cumulus cloud in its growing stage, the physical cloud radius is usually constant with height, while the updraft radius varies according to variations in the updraft speed, density, and the entrainment rate, as dictated by continuity principles. In general, the dormant cloud, updraft core and environment have the moisture, temperature and updraft properties as shown in Fig. 2. Notice that the temperature excess and updraft are concentrated in the core, but the mixing ratio excess is over the whole physical cloud. The regions of high moisture gradient, then, are along the side of the *physical cloud*, whereas the high temperature and updraft speed gradients are concentrated at the edge of the *updraft core*. This is the physical foundation for the different mixing rates for moisture and temperature (and momentum). Since the highest gradients of temperature and updraft speed occur at the edge of the *core*, the mixing rate for these parameters should be controlled by the updraft *core* radius. Since the strongest gradients of mixing ratio occur at the edge of the *physical cloud*, the mixing rate for that parameter should be controlled by the *physical cloud* radius.

5. Summary

In summary, one minor and two major points are made in response to Warner.

The minor point is that there *is* physical justification for using different mixing rates for moisture and heat in one-dimensional models. This distinction was not hidden in the computer program listing as implied by Warner, but rather was clearly stated by Weinstein and Davis (1968).

The major points are that 1) steady-state one-dimensional cumulus models were developed to describe the *gross* aspects of cumulus convection and should only be used where predictions of these gross aspects are of value; and 2) if model predictions of the internal cloud parameters are held up for comparsion with observations, the observations should be made in the first parcels of growing cumuli, for it is these parcels that the models come closest to simulating.

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