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

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In a recent paper Warner (1970) has compared observed internal cloud structure with that calculated with the steady-state cumulus model described by Weinstein and Davis (1968). He claimed that the model was unable to simultaneously predict the observed cloud top heights and the sampled liquid water contents. He then concluded that the concept of steady state is not applicable to actual clouds and that the simple idea of lateral entrainment is insufficient. I would like to comment on 1) Warner's criticism and use of the Weinstein-Davis model, and 2) his technique of comparing observed and model predicted cloud properties.

First of all, it must be recognized that Warner's criticism applies most directly to the Weinstein-Davis Pennsylvania State University (PSU) computational scheme and to a lesser extent to the physical basis of that model. Warner (1970) correctly pointed out several peculiarities of the model including different mixing rates for heat and moisture, the empirical nature of the treatment of precipitation mechanisms, and the unsatisfactory nature of the treatment of precipitation fallout. All these criticisms have since been rectified by the author (Cotton, 1970). Both the treatment of the precipitation mechanisms and the technique of precipitation fallout have considerable bearing on any comparison between model predictions and measured cloud structure. In particular, the assumption that all precipitation remains in the updraft until the terminal velocity of the median volume drop diameter exceeds the updraft velocity leads to serious errors in either the predicted cloud top height or the magnitude of the cloud water content in the upper 500 m of the cloud (Corkum and Lavoie, 1970). If all precipitation is retained in the updraft, the effective buoyancy is reduced by the weight of the water and the cloud top height is underpredicted. If a larger cloud radius is used to achieve the observed cloud top height, the subsequent reduction in the entrainment rate will result in an overprediction of cloud water content. The fact that the data analyzed by Warner (1970) excluded heavily raining clouds does not mean that the dynamics could not have been influenced by the presence of light rain or rain restricted to a small part of the cloud. The latter conditions were included in the data sample discussed by Warner (1955).

My second comment concerns the nature of Warner's comparison between observed and steady-state model predicted cloud properties. He begins by claiming that we must concern ourselves with the average water content, not its maximum value. I claim that this is an incorrect application of the basic concept of the steady-state model. The model as developed by Squires and Turner (1962) and applied by Weinstein and Davis (1968) is hypothesized to simulate the updraft structure of cumulonimbi. Since the updraft of cumulus clouds fills only a small fraction of the total cloud cross section, one would expect the model predicted properties to "best" agree with observed peak cloud properties and not the average values. Some evidence supporting the validity of this hypothesis was found by Corkum and Lavoie (1970), who calculated a linear correlation coefficient of 0.82 between observed *maximum* water contents in tropical cumulus and model predicted values when penetration data taken within 500 m of cloud top were not considered. At the same time they found the correlation coefficient between observed and predicted cloud top heights was 0.87.

Further support of the validity of this hypothesis may be seen in the comparison between EMB[1] Lagrangian cumulus model predictions and measured average cloud water contents in cumulus towers as discussed by Simpson and Wiggert (1969). They found their model (which incidentally is *not* simulated by operating the PSU model with a constant radius) predicted observed *average tower* water contents quite well. This may at first seem to be a contradiction. It must, however, be recognized that Simpson and Wiggert (1969) applied their model *only to the actively rising towers* of cumuliform clouds. Thus, the area of updraft to inactive portions of the tower is much closer to unity. Even so, Simpson[2] agreed that her model predictions of water content compared most favorably with the observed peak values in the actively rising towers.

Finally, I would like to quote Warner (1955) as follows:

[1] Experimental Meteorology Branch.
[2] Personal communication.

"Since the water content sometimes descended to zero well inside the cloud, the cloud being defined by failure to see the ground or the sky, it was thought inadvisable to use the average value throughout the traverse. . .

"It was found that the peak value, or possibly the mean of a series of peaks, was fairly reproducible from traverse to traverse at a fixed height and appeared to be a definite characteristic of the cloud."

It thus seems surprising that Warner should expect a model as simple as the steady-state model to predict anything but the most reproducible features of a cloud.

Although the simple concept of lateral entrainment employing an inverse radius dependence may at best be a first-order approximation, it is concluded that Warner's incorrect application of a version of the steady-state fails to justify his conclusion that the physical basis of the model is unsound. His work does, however, point out some major weaknesses of the Weinstein-Davis model and some possible limitations of simple one-dimensional Lagrangian calculations in general.

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