Reply

W. R. COTTON AND G. T. TRIPOLI

Department of Atmospheric Science, Colorado State University, Fort Collins 80523

22 February 1979 and 21 March 1979

Steiner (1979) contends that our conclusion [see Cotton and Tripoli (1978); hereafter referred to as CT] that the interaction of a cumulus cloud with an environment characterized by vertical shear of the horizontal wind is a major control on the prediction of cloud liquid water contents, is invalid because of the nature of the chosen cloud initiation mechanism. We welcome Dr. Steiner's comments since it allows us to clarify several points in the manuscript as well as interpret the results in the light of recently reported analyses of convective cloud observations.

Part of the controversy is a result of an error made on the description of the initial perturbation given on p. 1509. Instead of the given description of "Above the observed cloud base the air is assumed to be saturated through a depth of twice the cloud height.", the correct description should read, "Above the observed cloud-base height of 1500 m, the air is assumed to be saturated through a depth of 500 m or to a height of 2000 m AGL."

However, we agree with Steiner's contention that the main deficiency in the reported numerical experiments is a consequence of our choice of cloud initiation mechanism. The problem of cloud initiation was discussed in considerable length in Section 4. To overcome this deficiency, one must model both the micrometeorological and mesoscale meteorological processes leading to the initiation of a given cloud. Moreover, in order to perform such a simulation, one must have observations not only in the cloud layer, but also over the micro- and mesometeorological scales. In the absence of such supporting observations, we selected a simple moist bubble cloud initiation mechanism. A consequence of this bubble initiation mechanism or similar "thermal" bubble anomalies is that as the bubble develops buoyancy in the cloud layer, it immediately pinches itself off from any direct communication with the subcloud layer. With a far more sophisticated turbulence parameterization than we used, Lipps (1977) also experienced this difficulty in his

0022-4928/79/081610-02$04.50

simulation of tradewind cumuli. He suggested that the observed clouds were maintained by a field of horizontal convergence. We are preparing a manuscript describing numerical simulations of towering cumuli over Florida. In those numerical experiments, a stable cloud base could only be obtained by imposing a preexisting large-scale convergence field which is focused down to the cloud-scale.

As mentioned by CT, rather than "fiddle" with unknown surface conditions (i.e., surface temperature, surface moisture, low-level convergence) until a reasonable cloud-base rise rate was obtained, it was decided to stick with this initialization method. Being fully aware of the deficiencies of the method, we therefore chose to compare the peak predicted magnitude of $\bar{Q}_c/Q_A$ at a given level against those observed by Warner in the selected case. The adiabatic liquid water content Q_A was computed relative to the initial cloud-base height. The peak predicted values of the $\bar{Q}_c/Q_A$ occur just below the top of the rising cloud thermal in both the no-shear and sheared environmental simulations. Had we selected anything but the peak predicted values of $\bar{Q}_c/Q_A$, then we would be tempted to argue, as did Mason (1975), that Warner's horizontal traverses were through a cloud largely composed of the residues of earlier thermals and not fresh, wetter, actively rising thermals. This argument is not particularly strong, however, since Warner typically began his penetrations near the tops of actively rising towers and then descended while making horizontal traverses at successively lower levels.

It is our contention that the choice of initialization technique lends no particular advantage to either the three-dimensional cloud simulation in an initially stagnant environment or the simulation in a sheared environment, when the predictions of *peak* $\bar{Q}_c/Q_A$ are compared to Warner's first and uppermost observation level. This is particularly true since the same cloud top height was predicted in both simulations.

The interpretation of our results is as follows. In the unsheared case, the tops of the simulated clouds are protected from entrainment by a strong horizontally divergent region with an associated positive pressure anomaly. This divergent region acts as an "umbrella" which prevents environmental air from becoming entrained into the top of the rising tower nearly across the entire cloud width. In the sheared environment, the protected zone at the top of the rising cloud thermal is eroded by the effects of the cloud interacting with shear. The maximum cloud-top height, on the other hand, is largely controlled by the buoyancy in a small, somewhat wetter region of the cloud located in the "protected" upshear side of the cloud.

This interpretation is consistent with the findings of Warner (1977), Heymsfield, *et al.* (1978) and Ramond (1978). Warner (1977) found that an updraft core is often present in the upshear side of the cloud and that such a feature persists for periods of 10 to 15 min. Heymsfield *et al.* (1978) found moist adiabatic cores on the upshear portion of cumulus congestus towers in northeast Colorado. They hypothesized that the updraft acts to resist environmental flow at mid and upper levels and tends to divert the flow around the updraft protecting it from entrainment. On the downshear side of the cloud, a turbulent wake is formed which produces intense mixing in that region. Ramond (1978) diagnosed regions of positive pressure anomalies upwind of actively growing towers. He also inferred that the positive pressure anomaly forms a protective zone against entrainment which provides a mechanism for forming upshear undiluted cores. While the existence of undiluted cores was neither predicted by CT nor observed by Warner, nonetheless, the tendency to form protected zones on the upshear side of a cloud and over a relatively small area of the cloud may explain how clouds, in a sheared environment, can grow to observed heights yet contain small values of $\bar{Q}_c/Q_A$ averaged over the cloud width.

Therefore, we argue that, in spite of the inadequacies of our initiation mechanism, our earlier conclusions are valid and that an implication of these findings is that one-dimensional or axially symmetric models cannot be expected to adequately simulate cumuli if there is any shear present.

REFERENCES

Cotton, W. R., and G. J. Tripoli, 1978: Cumulus convection in shear flow-three-dimensional numerical experiments. *J. Atmos. Sci.*, **35**, 1503–1521.

Heymsfield, A. J., D. N. Johnson and J. E. Dye, 1978: Observations of moist adiabatic ascent in northeast Colorado cumulus congestus clouds. *J. Atmos. Sci.*, **35**, 1689–1703.

Lipps, F. B., 1977: A study of turbulence parameterization in a cloud model. *J. Atmos. Sci.*, **34**, 1751–1772.

Mason, B. J., 1975: Reply to Warner's "Discussion of Mason and Jonas' model of droplet growth in cumulus clouds." *Quart. J. Roy. Meteor. Soc.*, **101**, 176–178.

Ramond, D., 1978: Pressure perturbations in deep convection. *J. Atmos. Sci.*, **35**, 1704–1711.

Steiner, J. T., 1979: Comments on "Cumulus convection in shear flow-three-dimensional numerical experiments." *J. Atmos. Sci.*, **36**, 1609–1610.

Warner, J., 1977: Time variation of updraft and water content in small cumulus clouds. *J. Atmos. Sci.*, **34**, 1306–1312.