Comments "On the Freezing of Liquid Water in a Cloud"

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In a recent article, Orville and Hubbard (1973) raised "... doubts about the results of Weinstein's (1972) precipitation climatology . . .".¹ The purpose of this note is to remove or at least reduce the concern expressed by those doubts.

In describing the correct way to compute the latent heat released by freezing liquid water in cumuli, Orville and Hubbard make two points. The first is that the correct equation for computing the latent heat must be used. On that count the model used for the climatology cannot be faulted since it appears they used the correct equation and the model passed the test they proposed to check for this deficiency. Other steady-state cumulus models, particularly the version of the Weinstein-Davis model that resided on the Bureau of Reclamation's time-share system, did not pass the test. The model that Orville and Hubbard used in their paper is called the Great Plains Cumulus Model (GPCM). That model, the one used in the climatology, and the one used by the Bureau of Reclamation are all derived from the original Penn State University Steady State Cumulus Model that was described by Weinstein and Davis (1968). Since its publication, many workers have made substantial, sometimes valuable, improvements to the original model. The GPCM probably represents the best improvement. The model used for the climatology was also an improvement over the original Penn State version, although no new name was given to it. Just as it would be unreasonable to condemn the GPCM because it was derived from a source common to the Bureau of Reclamation's version of the Weinstein-Davis model, it is unreasonable to condemn any other version of the original model without appropriate test calculations. The model used in the climatology passed such a test. The test was mentioned in footnote 7 in the article by Orville and Hubbard, but I feel the point is worth mentioning here again.

The other point that Orville and Hubbard make concerning the method of computing the heat released by freezing is that even in natural cumuli where most of the liquid water freezes at very low temperatures, *some* rainwater freezes at relatively *high* temperatures. The foundation for their doubts about the climatology must rest on the fact that the model used in that investigation delays the freezing of all of the liquid

water, including all of the rainwater, in natural cumuli until the clouds reach the -25°C level. If the cloud never reaches -25°C , no rainwater is frozen and the computed natural cloud never realizes the thermal benefit of the latent heat of freezing of this rainwater. The GPCM simulates rainwater freezing "... via a Bigg (1953) freezing process . . ." that allows rainwater to start freezing at -5°C . Orville and Hubbard show in their Fig. 7 that this freezing, in an unrealistically large cumulus with no entrainment, does not become important in significantly warming the cloud until approximately -16°C (i.e., ~ 380 mb or 7.6 km). The -25°C level, where the climatology simulates freezing of all of the water in natural clouds, occurs at approximately 330 mb or 8.5 km in their Fig. 7. Thus, the underestimate of the thermal energy available to a natural cloud, in unrealistically large cumulus clouds with no entrainment, only occurs when that cloud is calculated to top out between -16 and -25°C or between 7.6 and 8.5 km. At higher temperatures the heat released by freezing precipitation is inconsequential, and at lower temperatures both models allow the cloud to realize the heat. Since the amount of water available to more realistic isolated cumuli for which the climatology was prepared is much less than that available to the hypothesized clouds with no entrainment, it is likely that the effect of freezing rainwater may not become important until temperatures are colder than -16°C . In this case the already narrow range of cloud top heights for which the climatology may be in error, is narrower still.

As stated by Orville and Hubbard, in those cases where the climatology is incorrect, the error is toward overestimating the ice phase seedability by underestimating natural cloud development. Although this would reduce the confidence one could place in the absolute magnitude of the seedability for the narrow range of conditions when very large natural cumuli would top out at between 7.6 and 8.5 km, the overall trend of all of the calculations, the trend upon which most of the climatology's conclusions are based, is not likely to be drastically altered.

REFERENCES

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Orville, H. D., and K. Hubbard, 1973: On the freezing of liquid water in a cloud. *J. Appl. Meteor.*, **12**, 671-676.

¹ All direct quotations are from the original paper by Orville and Hubbard.

- Weinstein, A. I., 1972: Ice phase seeding potential for cumulus cloud modification in the western United States. *J. Appl. Meteor.*, **11**, 202-210.
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