Reply

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Professor Orville's comments (Orville 1990) address the well-recognized duality of seeding effects on clouds: the introduction of ice opens a new path for the formation of precipitation ("static" effect), and the release of latent heat associated with the formation of ice ("dynamic" effect) increases the bouyancy of the glaciated air parcel. As shown by Orville through the model calculations referenced by him, for certain stratiform clouds the dynamic effects can be more subtle, and more important, than for the deep convective clouds for which the exploration of those effects was first proposed.

The conclusion Orville draws regarding the estimated precipitation enhancement potential of the Duero Basin is that the estimated increases given in our paper (Vali et al. 1988, abbreviated VKY in the following) are likely to be too low, because it is assumed in the calculations that the cloud dynamics (updrafts) are not altered significantly by the seeding. We feel that Orville's conclusion should be further qualified, and the potential magnitude of the effect should be examined.

In general, it does not appear well justified to assume that additional bouyancy will always lead to increases in precipitation. Variations in entrainment rates, in the scales of organization of internal motions, in the competition of particle growth versus transit time through the cloud, and in other factors, can cause deviations from a simple monotonic relationship between updraft velocity in the seeded area and overall precipitation efficiency for the system. The situation is especially complex for stratiform clouds, whose moisture supply may get a very small contribution from low-level convergence in the area where precipitation is being produced, or may be produced. Model results such as those quoted by Orville do show increases in precipitation with the inclusion of the dynamic effect, but extrapolation from those theoretical case studies to a general conclusion is not necessarily valid.

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Regarding the magnitude of the potential dynamic effect described by Orville, it must be emphasized that the stratiform clouds to which Orville's comments principally apply constitute a small fraction of the total sample included in the analyses. Using the definitions of "regions of potential" given in VKY, the increases calculated for all stratiform clouds by the two different models amounted to only 1.3% and 2.6%, respectively, for the days of seeding (cf. Table 4 of VKY), and 0.064% and 0.13% of the annual precipitation (Table 5 of VKY). Five- to tenfold larger potential increases in precipitation would be required for the stratiform clouds to match those estimated for other cloud types. Much smaller effects are shown by the model calculations of Orville et al. (1984, 1987). But, even with tenfold increases over the pool and stream models of VKY, the total potential precipitation increase for the Duero Basin would still be only 1.1% or 2.5%, respectively.

Changing the conditions which are considered suitable for seeding, according to the arguments of Orville, still does not yield much of a change in final results. In the total sample for stratiform (class A) clouds at temperatures $< 0°C$, there were $> 10\ cm^{-3}$ cloud droplets in a cloud volume only 2.75 times greater than where the liquid water content was $> 0.1\ g\ m^{-3}$. Thus, accepting clouds as tenuous as those with $10\ cm^{-3}$ cloud droplets as capable of producing additional precipitation through the process described by Orville, and assuming that all those regions would yield about the same amount of additional precipitation as has been estimated for the regions of potential (with the tenfold increase discussed in the previous paragraph also included), the potential increase in annual precipitation is still estimated as only ranging from 1.8% to 3.9%.

To underscore Orville's observation that the "processes are extremely time dependent," we point out that there were very few observations of stratiform clouds colder than 0°C where cloud droplets were present without any ice particles. Only thin, elevated layers had those conditions. In the deeper clouds, ice was usually present everywhere. In the total Class A sample set, 26% of clouds with $> 10\ cm^{-3}$ droplets had the time-dependent balance between vertical motions, droplet and ice particle concentration has to be considered. There is also a practical consequence of the time dependence: seeding has to take place in that narrow time interval when there is still liquid water present. In addition, all of the water has to be converted to ice for the shift in saturation to occur. Because the detection of the low liquid water contents, or of the small vertical motions giving rise to them, is not readily accomplished with any current technology, the logistical difficulties of seeding these regions would be quite extreme.

The many reservations expressed above are not intended as a defense of the simple, and admittedly incomplete, models we employed, as opposed to the more complete calculations possible for select cases. We also recognize that the same complexities that weaken Orville's conclusion also weaken the validity of the numerical adjustments presented here, or even the prospect that the dynamic effect can be accounted for as a multiplier of the estimates derived in VKY. Nonetheless, we used such a simple exercise, with highly exaggerated multipliers, to show that the expected effects are relatively small, so that the overall conclusions of VKY would not change with respect to the Duero Basin.

In the spirit that VKY emphasized the importance of their approach over the specific results for the Duero Basin, the factors brought to light by Orville also have more general implications. No doubt, methods for estimating changes in precipitation due to seeding can be improved beyond those given in our paper, and newer analyses will perhaps include the energy terms whose role Orville emphasizes.

REFERENCES

Orville, H. D., 1990: Comments on "Estimate of precipitation enhancement potential for the Duero Basin of Spain." *J. Appl. Meteor.*, **29**, 188–189.

——, R. D. Farley and J. H. Hirsch, 1984: Some surprising results from simulated seeding of stratiform-type clouds. *J. Climate Appl. Meteor.*, **23**, 1585–1600.

——, J. H. Hirsch and R. D. Farley, 1987: Further results on numerical cloud seeding simulations of stratiform-type clouds. *J. Wea. Modif.*, **19**, 57–61.

Vali, G., L. R. Koenig and T. C. Yoksas, 1988: Estimate of precipitation enhancement potential for the Duero Basin of Spain. *J. Appl. Meteor.*, **27**, 829–850.