Comments on the Climax and Wolf Creek Pass Cloud Seeding Experiments[1]

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ABSTRACT

The physical hypotheses for the cloud seeding experiments carried out by Colorado State University in the Colorado Rockies (Climax I and II and Wolf Creek Pass) in the 1960's are critically examined. Airborne measurements over the Rockies have shown that the concentrations of ice particles in the natural clouds are often much greater than originally assumed; consequently, the conditions under which it might be possible to increase precipitation by artificial seeding are probably much more limited than previously supposed. There appears to be no firm evidence to support the contention that 500 mb temperatures are a good measure of cloud-top temperatures over the Rockies. Finally, examination of a more extensive data set than previously used fails to substantiate the claim that precipitation over the Rockies decreases as 500 mb temperatures increase above certain values.

1. Introduction

One of the few experiments that has been widely accepted by the scientific community as demonstrating significant increases in precipitation due to artificial seeding was carried out on winter orographic clouds in the Rocky Mountains of Colorado under the leadership of Professor Lewis O. Grant. These experiments are generally referred to as Climax I (Grant and Mielke, 1967; Grant *et al.*[2]; Mielke *et al.*, 1970), Climax II (Chappell *et al.*, 1971; Mielke *et al.*, 1971) and the Wolf Creek Pass Experiment (Grant and Elliott, 1974;

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[2] Grant, L. O., P. W. Mielke, C. F. Chappell, L. W. Crow, J. L. Rasmussen, W. E. Shobe, H. Stockwell and R. A. Wykstra, 1969: An operational adaptation program of weather modification for the Colorado river basin. Bureau of Reclamation Interim Report, 99 pp. [Available from BOF, Bldg. 67, Denver Federal Center, Denver, CO 80225.]

Mielke *et al.*, 1977); we will refer to them collectively as the Colorado State University (CSU) experiments.

The general acceptance of the results reported by the CSU workers has been due, in large part, to the fact that there appeared to be strong physical arguments as well as statistical evidence for believing that under certain atmospheric conditions seeding should enhance precipitation in the Colorado Rockies. In an earlier paper one of us (Rangno, 1979) has shown that the conclusion (based on statistical analyses) that seeding produced large increases in precipitation in the Wolf Creek Pass Experiment is open to serious doubt. In this note, we raise a number of questions concerning the physical concepts that have been proposed in support of cloud seeding effects in the CSU experiments.

2. Physical basis for the CSU experiments

The principal physical arguments proposed by Grant and his co-workers to support their contention that there is a potential for precipitation enhancement in the Colorado Rockies may be summarized as follows:

1) Ground-based measurements of ice nuclei indicated that at cloud-top temperatures $\gtrsim -20°C$ the concentrations of ice particles in clouds over the Rockies should fall below the optimum concentrations required for the efficient release of precipitation.

2) On the assumption that 500 mb temperatures are representative of cloud-top temperatures over the Rockies, it was concluded that in winter there are many occasions when cloud-top temperatures are $\gtrsim -20°C$ and therefore that artificial seeding should enhance precipitation.

3) These ideas received support from Chappell's (1970) observations that daily precipitation amounts decreased markedly as the 500 mb temperatures increased from -23 to $-18°C$ at Wolf Creek Pass and above $-20°C$ at Climax. This was attributed to decreasing concentrations of active ice nuclei with increasing temperature.

These three cornerstones of CSU's physical arguments are reassessed in the following sections.

3. Cloud-top temperatures and ice particle concentrations

In a laudable effort to provide a physical explanation for the statistical results obtained in the CSU experiments (which indicated large increases in precipitation when seeding was carried out at 500 mb temperatures $\gtrsim -20°C$) Grant *et al.*[2] attempted to answer the important question: what is the optimum concentration of ice particles required for the most efficient release of precipitation in winter storms in the Colorado Rockies? Assuming that the diffusion of water vapor dominates in the conversion of liquid drops to ice, Grant *et al.* concluded that the optimum concentration of ice particles is obtained by equating the rate of growth of the ice particles to the rate of production of liquid condensate. Their calculations indicated that at $-20°C$, and with an updraft speed of 1 m s^{-1}, ice particles 1000 μm in maximum dimensions would have to be present in concentrations of $\sim 30\ \ell^{-1}$ for the optimum release of precipitation.

If we should now assume, as did Grant *et al.*, that the natural concentration of ice particles in clouds with tops at $-20°C$ is the same as the measured concentration of active ice nuclei at this temperature ($\sim 1\ \ell^{-1}$), we would conclude, as they did, that the natural concentrations of ice particles at this (and higher) temperatures are below the optimum required for the efficient release of precipitation; therefore, artificial seeding should increase precipitation. However, direct airborne measurements in winter clouds over the Rockies have since shown that the ice particle concentrations bear little or no relation to the measured ice nucleus concentrations, and that the ice particle concentrations often exceed Grant *et al.*'s optimum concentrations even at quite high temperatures.[3,4] For example, at $-20°C$, ice particle concentrations ranging from 20–200 ℓ^{-1} have been measured.[5] Under these conditions, the introduction of artificial ice nuclei (particularly from ground generators) is unlikely to significantly affect the structures of the clouds or the production of precipitation.

4. Cloud-top and 500 mb temperatures

In the statistical analyses of the CSU cloud seeding experiments the 500 mb temperature has been used as the critical partitioning parameter (Grant and Mielke, 1967; Mielke *et al.*, 1970). The physical justification for this is the claim that 500 mb temperatures for winter storms over the Colorado Rockies are a reliable measure of cloud-top temperatures (Grant and Mielke, 1967). Since there is no *a priori* reason why this should be so, such an assertion has to be based on empirical evidence. The only evidence that has been quoted by CSU workers to support a relationship between cloud-top and 500 mb temperatures is the study of Furman (1967). For example, Grant and Elliott (1974) state: "Furman (1967), using radar and other visual and aircraft observations, has shown

[3] Hobbs, P. V., L. F. Radke, J. R. Fleming and D. G. Atkinson, 1975: Airborne ice nucleus and cloud microstructure measurements in naturally and artificially seeded situations over the San Juan Mountains of Colorado. Res. Rep. X, Cloud Physics Group, University of Washington, 89 pp.

[4] Marwitz, J. D., W. A. Cooper and C. P. R. Saunders, 1976: Structure and seedability of San Juan storms. College of Engineering, University of Wyoming, Final Report to Bureau of Reclamation, 326 pp.

[5] Ice particle concentrations considerably in excess of measured ice nucleus concentrations are attributed to *ice enhancement* processes. Ice enhancement has been observed in many locations (see, e.g., Mossop, 1970; Hobbs and Atkinson, 1976; Hallett *et al.*, 1978; Herzegh and Hobbs, 1979).

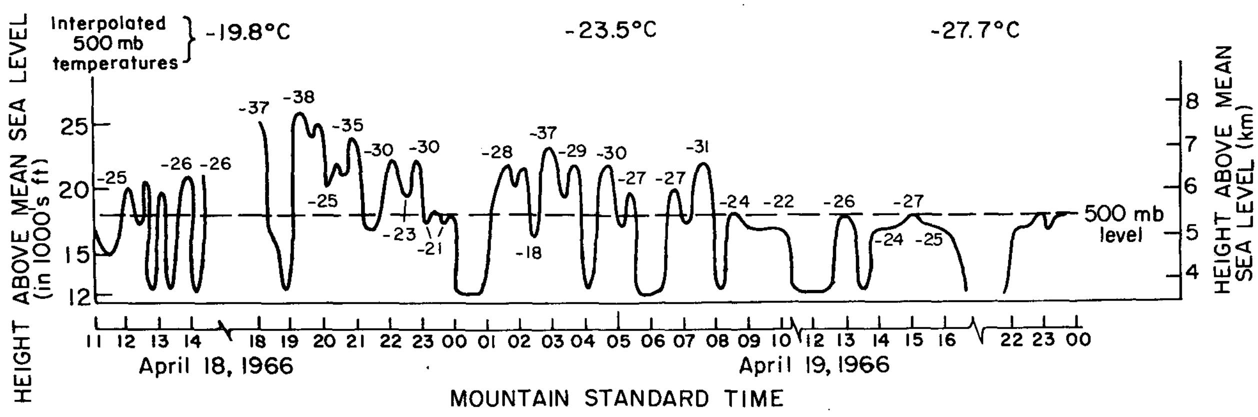

FIG. 1. The curve shows the height of the 3 cm radar echo tops for a period of about 37 h at Climax (data from Furman, 1967). The numbers on the curves are derived air temperatures at various heights. Also shown is the height of the 500 mb level and (at top of the diagram) the interpolated temperatures at the 500 mb level at three times.

that the 500 mb level is close to the mean elevation of the wintertime orographic cloud tops near Climax, Colorado." In fact, Furman does not discuss any aircraft observations, and his studies (involving just three storms which followed similar paths into the Rockies) were carried out in spring, not winter. More importantly Furman, prudently it appears to us, drew no conclusion concerning the relationship between 500 mb and cloud-top temperatures.

Shown in Fig. 1 is the only time section for Climax presented by Furman; it shows 3 cm radar echo tops (hereafter we will follow Furman and call these "cloud" tops) for a period of 37 h. We have added to the diagram the 500 mb heights and the temperatures at the "cloud" tops; the latter were deduced assuming a saturated adiabatic lapse rate about the 500 mb temperature. It can be seen that the "cloud"-top temperatures fluctuated rapidly between extreme values of -38 and -18°C, whereas the 500 mb temperatures varied only slowly from about -20°C near the beginning of the time period shown in Fig. 1 to about -28°C near the end.

From Furman's observations, it appears that 500 mb temperatures are of little predictive value for assessing cloud-top temperatures in the Colorado Rockies. For example, based on the 500 mb temperature and Grant and Elliott's (1947) "cloud seeding window" criterion (i.e., cloud-top temperatures between -10 and -25°C) the clouds would have been assessed as suitable for seeding from the beginning of the time period shown in Fig. 1 to about 0900 GMT, and unsuitable for seeding thereafter. From the "cloud"-top temperatures, on the other hand, one would have deduced that the clouds were fluctuating rapidly in temperature but were generally not within Grant and Elliott's "cloud seeding window."

The dichotomy presented by 500 mb and cloud top temperatures observed during the conduct of the Colorado River Basin Pilot Project (CRBPP) was directly responsible for several changes in the criteria for seeding during the course of CRBPP.[6] During most of the first season of the CRBPP, 500 mb temperatures were used, in the second and third seasons cloud top temperatures were employed, and in the fourth and fifth seasons there was a reversal to 500 mb temperatures! These oscillations occurred because it was not clear whether the seeding criteria for the CRBPP should have corresponded to the categories of 500 mb temperature under which precipitation increases had been reported on seeded days during the CSU experiments, or whether it should have been based on cloud-top temperature as suggested by the CSU physical arguments. The problem was acutely apparent to forecasting personnel of the CRBPP when presented with deep cloud systems with low cloud-top temperatures, but with 500 mb temperatures $\geqslant -23$°C. With the 500 mb criterion such systems qualified for seeding, but with cloud-top temperature as the criterion they did not qualify.

5. Precipitation and 500 mb temperatures

An important link in CSU's physical arguments concerning 500 mb temperatures and the production of precipitation was Chappell's (1970) conclusion that as the 500 mb temperatures increase from about -23 to -18°C at Wolf Creek Pass and from -20 to -15°C at Climax, precipitation decreases markedly. Chappell's evidence in support of this conclusion is shown in Fig. 2a. Shown in Fig. 2b are further data that we have assembled for three stations in the Colorado Rockies. In general, it can be seen that this larger data set does not support the view that precipitation decreases as 500 mb temperatures increase over the Rockies.

Chappell used a 4° running mean in deriving the curves for Wolf Creek Pass and Climax shown in Fig. 2a and he totaled precipitation amounts over 24 h periods, starting at 1000 LST. Precipitation

[6] Hjermstad, L. M., 1975: Final comprehensive operations report, 1970–1975. Rep. to Bureau of Reclamation, 161 pp.

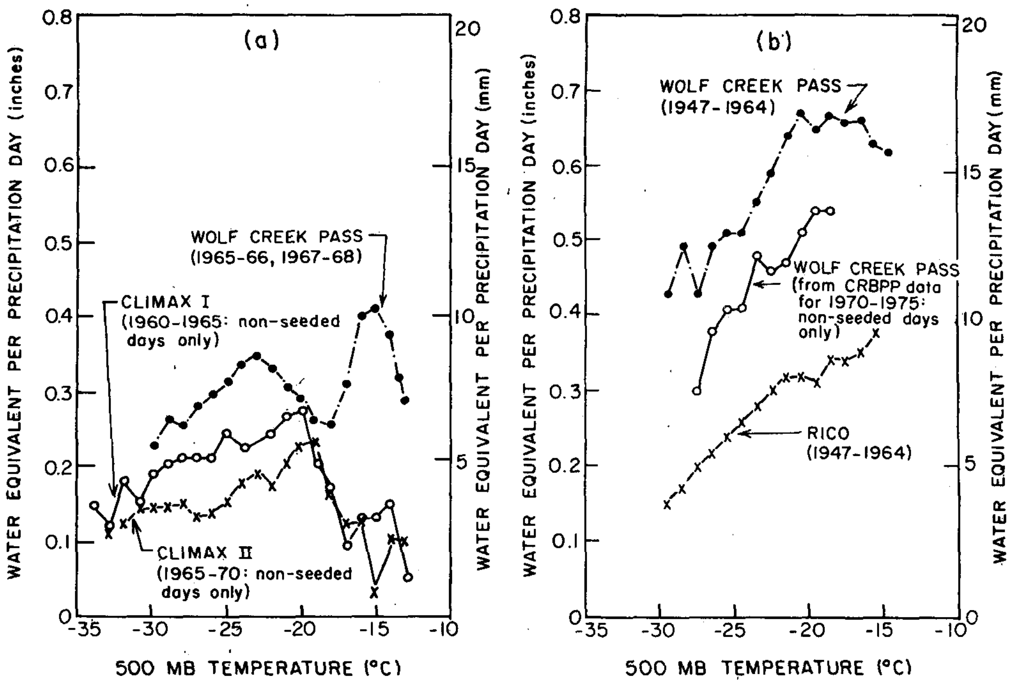

FIG. 2. Precipitation amounts versus 500 mb temperatures for stations in the Colorado Rockies. (a) Data presented by Chappell (1970), (b) an expanded data set.

amounts in the periods 1000–2200 LST and 2200–1000 LST were compared and the 12 h period with the greater precipitation amount was used to determine whether the 1700 LST or 0500 LST 500 mb temperature was used in Fig. 2a. We used similar techniques for the CRBPP data shown in Fig. 2b. The data for Wolf Creek Pass and Rico were compiled from cooperative gages, maintained by NOAA, which are read once a day; in these cases, the mean 500 mb temperature for the preceding 24 h period has been used.

6. Conclusions

In this note we have reviewed the key physical arguments that Grant and his co-workers have proposed to support their assertion that a significant potential exists in the Colorado Rockies for increasing winter precipitation by cloud seeding.

Airborne measurements have shown that the concentrations of ice particles in clouds over the Colorado Rockies are often very much greater than previously assumed. Consequently, the conditions under which it might be possible to increase precipitation by artificial seeding are probably much more limited than Grant *et al.*[2] or Grant and Elliott (1974) suggest.

The evidence that has been quoted by Grant and his co-workers to support the contention that the 500 mb temperature is a good measure of cloud-top temperature in the Colorado Rockies has been reviewed and found to be inadequate to substantiate this claim.

We have also shown that the previously claimed relationship between precipitation and 500 mb temperatures is not supported by a wider data set for the Colorado Rockies.

It should be noted that the statistical analyses of the Climax seeding experiments, which are independent of the physical hypotheses, have not been addressed in this note. However, it has been pointed out in a previous paper (Rangno, 1979) that the statistical analyses of the Wolf Creek Pass experiment led to the apparent misperception of a seeding effect in that area. In view of the importance that has been placed on the Climax results, an independent evaluation of the statistical results of these experiments is urgently needed.

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