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REVIEW OF WARM CLOUD MODIFICATION

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The status of modification of precipitation from warm clouds has been discussed in an excellent review paper by Cotton (1982). Later progress on the topic was reviewed by Ramanamurty (1984) and Czys and Buintjes (1994). The present scenario of weather modification has been discussed by Orville (1995) in his report on the WMO Scientific Conference on Weather Modification held at Paestum, Italy during 30 May – 4 June 1994.

Many of the potential rain-bearing clouds in tropical and semi-tropical countries are convective in nature and their tops often not exceeding the height of the freezing level. In these clouds the cloud physical processes involved in the initiation and development of rain are condensation, collision-coalescence, and break-up. The possibility of modifying precipitation from warm clouds has been studied extensively, both theoretically and experimentally with conflicting results. Most of the warm rain processes have been simulated in the laboratory as well as in modeling work. Although favourable from the theoretical point of view, the experiments for rain enhancement from warm clouds, conducted up to the present time, do not have the necessary physical observations for clear-cut evaluation and possible technology transfer (WMO, 1994).

Although most of the warm cloud modification experiments have not provided conclusive scientific evidence of seeding effects, some of the experiments (Braham, 1957; Biswas and Dennis, 1971; Dennis and Koscielski, 1972; Murty, 1989; Bruintjes et al., 1993; Cooper et al., 1994; Czys and Bruintjes, 1994) leave the impression that the effects are generally consistent with the physical hypothesis of warm cloud modification, i.e., alteration of condensation/collision-coalescence/break-up growth processes by seeding clouds either with small water droplets or hygroscopic materials thereby enhancing the precipitation efficiency of the cloud systems leading to enhancement of rain. Seeding effects beyond those expected on the coalescence may also be apparently possible, e.g., dynamic effects which could possibly be induced in conjunction with the latent heat of condensation, or from more active conversion of supercooled water or ice or for both reasons (Woodcock and Spencer, 1967; Clark et al., 1972; Murty et al., 1975; Parasnis et al., 1982; Cotton, 1982; Czys and Bruintjes, 1994).

Even though some of the experiments offer some proof of the physical concepts of warm cloud modification, the contributions of the resulting rainfall to water supplies are generally insufficient. The central goals facing the weather modification scientific community are to (i) demonstrate to the satisfaction of the users, scientists and statisticians that the net rainfall can beneficially be increased from the larger and complex cloud systems over larger areas and (ii) to prove whether the microphysics or the dynamics of the cloud systems can be sufficiently and predictably altered artificially through seeding. Satisfying proof of the warm cloud modification hypothesis will come only with the systematic cloud physical measurements from well designed experiments and these observations could eventually provide the direct physical evidence for the modification of precipitation from warm clouds.

The progress on the simulation of warm rain processes including the seeding effects has been reviewed by several investigators (Cotton, 1982; Tuition et al., 1994; Cays and Brunettes, 1994). In a recent report on the Sixth WMO Scientific Conference on Weather Modification held at Paestum, Italy during 30 May – 4 June 1994, Orville (1995) stated that numerical simulation of cloud and precipitation processes support the physical studies, sometimes provide an explanation of the results, and suggest other experiments to pursue. A broader use of three-dimensional models was evident, some showing the dispersal of seeding agents and providing realistic cloud-seeding results.

The success of field experiments is difficult to assess and they cannot be repeatedly performed in clouds of the same dynamical and microphysical characteristics. Similarly, it is always not feasible to adopt identical seeding methodology in field experiments and often varies in size spectra of the nuclei, total quantity of seeding material, time and location of seeding, and the techniques of injecting the seeding material. These problems could be partly circumvented by evaluating each individual experiment with precise in-situ and remote measurements. This approach is expensive and often not feasible. Some of these problems could be overcome to some extent, through simulation of the precise seeding methodologies in realistic numerical cloud models. Such theoretical studies should form as major components in the analysis of field experiments (Cotton, 1982; Rasmussen et al., 1989). However, it is to be recognized that the most sophisticated numerical cloud model at the present time will not be able to simulate precisely the physical and dynamical processes representative of the actual natural conditions in real clouds.

Theoretical investigations of cloud seeding require solving of microphysical and dynamical processes using numerical methods that are reliable enough to simulate overall cloud development and accurate enough to capture the subtle effects of seeding (Tzivion et al., 1994). The basic assumption in hygroscopic seeding is that introduction of hygroscopic particles promotes formation of relatively larger drops by nucleation and condensation processes that quickly reach sizes where collection and collisional-breakup processes become active. The latter produce relatively high concentrations of fragments large enough to accelerate further growth by collection. Thus, it is assumed that the microphysical processes responsible for warm rain promotion (nucleation, condensation, collisional-coalescence/breakup) be treated with maximum accuracy.

Results of simulations of seeding with hygroscopic nuclei using an axisymmetrical model with detailed microphysics of warm cloud processes, including collisional breakup indicated that the collisional breakup process is very important in warm clouds and inhibits the growth of drops to large sizes where spontaneous breakup is significant (Tzivion et al., 1994). Simulation of hygroscopic seeding in maritime clouds produced no significant effects whereas in continental clouds the seeding effects were very significant. The size of the seeded particles and the timing of seeding were found to be crucial parameters. Premature seeding could have negative effects. Under optimal seeding conditions up to 71 per cent increase in total rainfall was obtained.

Results of the Indian Experiment suggested that warm cloud responses to salt seeding are critically dependent on the cloud physical characteristics (vertical thickness and liquid water content). Clouds with vertical thickness > 1km, with liquid water content > 0.5 gm m^{-3} when seeded with salt particles (modal size 10μm) produced increases in rainfall of 24 per cent significant at 4 per cent level. Shallow clouds (vertical depth < 1 km, liquid water content < 0.5 gm m^{-3}) when seeded with salt particles showed tendency for dissipation leading to decrease in rainfall. The cloud physical measurements made in not-seeded (Control) and seeded (Target) clouds showed that the giant condensation nuclei, width of cloud droplet spectra, concentration of large cloud droplets (diameter > 50 μm) and the cloud liquid water content in the target clouds showed increases ranging from 50 to 150 per cent. The Chloride and Sodium ion concentrations in the cloud and rain water samples collected from the aircraft also showed increases ranging from 110 to 165 per cent. The results are statistically significant and they appear to provide the physical evidence in support of the results of the statistical evaluation of the 11-year experiment (Murty, 1989). These experimental results and the results of the theoretical studies simulating the hygroscopic seeding effects in the convective cloud (Tzivion et al., 1994) are in agreement and would serve as important landmarks for designing of future good field experiments of warm cloud modification.

It is encouraging to note the results of the most recent randomized warm cloud modification experiments carried out during 1991-92 summer season in two regions in South Africa, the Bethlehem region on the Highveld (where cloud base temperatures are approximately +7^{o}C) and the Carolina region in the eastern Transvaal (where cloud base temperatures are approximately +10^{o}C). The seeding was carried out using 1000 g pyrotechnic flares. The flare composition of 5 per cent Magnesium, 10 per cent Sodium Chloride, 65 per cent Potassium Perchlorate, and 2 per cent Lithium Carbonate, and produced a combustion product which was 21 per cent Sodium Chloride, 67 per cent Potassium Chloride, and 12 per cent Magnesium Oxide (Mather and Terblanche, 1982). Flares were ignited at the cloud base level in strong updrafts. A maximum of 10 flares were used in each seed case. A total of 50 seeding trials were conducted, 25 of which were seeded and 25 unseeded. Twenty-one experiments were carried out in the Bethlehem area and the other 29 were carried out in the Carolina area.

The experimental units in either the Bethlehem or Carolina areas were defined by multicellular convective systems that already laid a radar echo of at least 30dBz. Radar estimated rain mass was calculated for the lowest radar scan (1.5^{o} elevation) and at the 6kms level above the mean sea level (approximately -10^{o}C). Rain masses were sorted into 10 minute time windows starting 10 minutes before and ending 1 hour after the seed-no-seed decision. Statistical analysis indicated that the rain masses in seeded storms are higher and the differences are significant at 10 per cent level (Bruintjes et al., 1993). Aircraft measurements of cloud droplet spectra in seeded and not-seeded clouds were also made which indicated differences between the spectra in seeded and not-seeded clouds (Czys and Bruintjes, 1994; Cooper et al., 1994; Mather and Terblanche, 1994).

Thailand has carried out warm cloud modification experiments since 1975 for stimulating the convection by means of seeding with chemicals having exothermic endothermic properties (WMO, 1990). A long term cloud seeding programme to augment additional water has been planned (Surakul et al., 1989; Medina and Rasmussen, 1989).

References

Biswas, K.R. and A.S. Dennis, 1971: Formation of rain shower by salt seeding. *J. Appl.meteor*. **4**, 780-784.

Braham, R.R. Jr., J. Baltan and H.R. Byers, 1957: Artificial nucleation of cumulus clouds, clouds and weather modification: a group of field experiments. In: *Cloud and Weather Modification, Meteor. Monogr*. **2** (11), 47-85.

Bruintjes, R.T., G.K. Mather, D.E. Terblanche and F.E. Steffens, 1993: A new look at the potential of hygroscopic seeding in summertime convective clouds. *Proc. 1993 National Conf. Irrigation and Drainage Engineering*, Park City, Utah, USA, 21-23 July ASCE, 496-503.

Clark, R.S., P.St. Amand and T.L. Wright, 1972: Modification of warm convective clouds by hygroscopic and hydrophobic materials. *Proc. Third Conference on Weather Modification*, 26-29 June 1972, Rapid City, South Dakota, USA, 179-181.

Cotton, W.R., 1982: Modification of precipitation from warm clouds – A review. *Bull. Amer. Meteor. Soc*. **63**,146-160.

Cooper, W.A., R.T. Bruintjes and G.K. Mather, 1994: Some calculations pertaining to hygroscopic seeding with flares. *Proc. Sixth WMO Scientific Conference on Weather Modification*, Paestum, Italy, 30 May – 4 June 1994, 677-680.

Czys, R.R. and R.T. Bruintjes, 1994: A review of hygroscopic seeding experiments to enhance rainfall. *J. Weather Modification* **26**, 41-52.

Dennis, A.S. and A. Koscielski, 1972: Height and temperature of first echoes in unseeded and seeded convective clouds in South Dakota. *J. Appl. Meteor*. **11**, 994-1000.

Mather, G.K. and D.E. Terblanche, 1992: Cloud physics experiments with artificially produced hygroscopic nuclei. *Proc. Eleventh International Conference on Clouds and Precipitation*, Montreal, Canada, 17-21 August 1992, 147-150.

Mather, G.K. and D. Terblanche, 1994: Initial results from cloud seeding experiments using hygroscopic flares. *Proc. Sixth WMO Scientific Conference on Weather Modification*, Paestum, Italy, 3 May – 4 June 1994, 687-690.

Medina, G.K. and R. Rasmussen, 1989: Preliminary design and statistical evaluation plan for the Thailand Applied Atmospheric Resources Research Programme. *Proc. Fifth WMO Scientific Conference on Weather Modification and Applied Cloud Physics*, Beijing, China, 8-12 May 1989, 529-532.

Murty, A.S.R., A.M. Selvam and Bh.V.R. Murty, 1975: Summary of observations indicating dynamic effect of salt seeding in warm cumulus clouds. *J.Appl. Meteor*. **14**, 629-637.

Murty, A.S.R., 1989: An overview of warm cloud modification research in India. *Proc. Fifth WMO Scientific Conference on Weather Modification and Applied Cloud Physics*, Beijing, China, 8-12 May 1989, 521-524.

Orville, H.D., 1995: *Report on the Sixth WMO Scientific Conference on Weather Modification*, Paestum, Italy, 30 May – 3 June 1994.

Parasnis, S.S., A.M. Selvam, A.S.R. Murty and Bh.V.R. Murty, 1982: Dynamic responses of warm monsoon clouds to salt seeding. *J. Weather Modification* **14**, 35-37.

Ramanamurty, Bh.V., 1984: *Review of warm cloud modification*. WMO/TD-No.5, World Meteorological Organization, Geneva, Switzerland, 43pp.

Rasmussen, R.M., B.A. Silverman, T. Clark and W.D. Hall, 1989: Evaluation of seeding techniques for tropical clouds using cloud model. *Proc. Fifth WMO Scientific Conference on Weather Modification and Applied Cloud Physics*, Beijing, China, 8-12 May 1989, 209-212.

Surakul, S., S. Warit, W. Khantiyanan and B.A. Silverman, 1989: The Thailand Applied Atmospheric Resources Research Programme. *Proc. Fifth WMO Scientific Conference on Weather Modification and Applied Cloud Physics*, Beijing, China, 8-12 May 1989, 567-570.

Tzivion, S., T. Raisin and Z. Levin, 1994: Numerical simulation of hygroscopic seeding in a convective cloud. *J. Appl. Meteor*. **33**, 252-367.

World Meteorological Organization (WMO), 1990: *Report of the Seventeenth Session of the Executive Council Panel of Experts/CAS Working Group on Physics and Chemistry of Clouds and Weather Modification Research*, Geneva, 19-23 November 1990, WMP Report No. 16, World Meteorological Organization, Geneva, Switzerland, 50pp.

World Meteorological Organization (WMO), 1994: *WMO Statement on the Status of Weather Modification, Proc. Sixth WMO Scientific Conference on Weather Modification*, Paestum, Italy, 30 May 1994-4 June 1994, Appendix – 1-9.

Woodstock, A.H. and A.T. Spencer, 1967: Latent heat released experimentally by adding sodium chloride particles to the atmosphere. *J. Applied Meteor*. **6**, 95-101.