Modification of Precipitation from Warm Clouds—A Review[1]

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Abstract

This review is begun with a brief summary of the current status of our understanding of the physics of precipitation in warm clouds. The impact of warm-cloud precipitation processes on the evolution of the ice phase in supercooled clouds also is discussed.

This is followed by a review of experimental attempts to modify the microstructure of warm clouds. Modeling studies of warm cloud modification and observational studies of inadvertent warm cloud modification also are drawn upon to further elucidate the physics of warm cloud modification. The hypotheses, and evidence, for dynamic modification of warm clouds are then discussed. A few brief comments on modeling of warm cloud processes also are given. These comments are intended to serve as a warning to the nonmodeler to be very cautious in taking the results of the modeling studies at face value. Finally, the review is concluded with specific recommendations regarding the current status of warm cloud modification, and future directions for the scientist and the weather modification practitioner.

1. Introduction

The motivation for developing or improving a technology for enhancing precipitation from warm clouds comes mainly from peoples in tropical and semi-tropical, arid regions. During drought periods or during the "normally" low rainfall periods in such regions, often the only clouds present are strictly warm cumuli. The feeling of the peoples in such regions is that even a small amount of rainfall would help alleviate the severity of the drought or bring some comfort during the dry period. This is not to say that these are the only regions of the world in which warm cloud precipitation modification is desired, or that a potential for modification exists.

In this review, I refer to warm clouds as those clouds in which the ice phase does not play a significant role in the precipitation process. The discussion, however, will not be restricted to clouds whose tops are wholly below the height of the 0°C isotherm. Instead, I limit the discussion to clouds in which the collision and coalescence process (warm rain process) is the dominant precipitation mechanism.

I begin the review by briefly summarizing the status of our current understanding of the physics of precipitation formation in warm clouds. The impact of warm-cloud precipitation processes on the evolution of the ice phase in supercooled clouds also will be discussed. As we shall see later, the fact that warm cloud processes affect the evolution of the ice phase may have bearing upon our interpretation of experiments investigating inadvertent and advertent modification of warm clouds.

I then review experimental attempts to modify the microstructure of warm clouds. Modeling studies of warm cloud modification and observational studies of inadvertent warm cloud modification also are drawn upon to further elucidate the physics of warm cloud modification.

The hypotheses, and evidence, for dynamic modification of warm clouds are then investigated. Finally, I conclude with specific recommendations regarding the current status of warm cloud modification and future directions for the scientist and the weather modification practitioner.

2. A summary of the current status of our understanding of warm-cloud precipitation processes

Braham, Battan, and Byers (1957) pointed out that the most notable feature of maritime, tradewind cumuli was their ability to produce rain when only a few kilometers thick. Squires (1956, 1958) remarked on the differences in droplet concentrations in cumuli formed in maritime and continental airmasses. He introduced the concept of colloidal stability of warm clouds whereby similar clouds forming in a maritime airmass are more likely to produce rain than clouds forming in a continental airmass. Thus, maritime clouds are less colloidally stable than are their continental counterparts. The relationship between the cloud droplet concentration and the cloud nucleus population was demonstrated by Twomey and Squires (1959) and Twomey and Warner (1967). Hence, in the nucleus-rich continental airmass, a given liquid water content must be distributed over numerous small droplets having small collection kernels or collection cross sections (i.e., low terminal velocities, collection efficiencies, and cross-sectional areas).

Recently, Johnson (1980a) noted that cloud-base temperature also influences the activation of cloud droplets. Other things being the same (i.e., aerosol distribution, cloud-base updraft velocity), clouds with colder cloud bases will activate more cloud droplets than clouds having warmer bases. This is a consequence of the nonlinear variation of saturation vapor pressure with temperature, which results in higher peak supersaturations in cold-based clouds than warm-

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based clouds that are otherwise the same. It is the direction of this effect that is most interesting, since the temperature effect will accentuate the tendency for colloidal stability in continental clouds if those clouds also have cold bases (a common occurrence in mid-latitude, continental regions). The aerosol distribution and updraft velocity at cloud base, however, remain as the most important factors controlling the concentration of activated droplets and, hence, the colloidal stability of a cloud.

For some time, it was thought that collision and coalescence could not proceed until droplets exceeded 19 μm in radius (Hocking, 1959). More recent calculations of collision efficiency by Klett and Davis (1973) suggest that droplets smaller than 19 μm in radius do exhibit finite collection efficiencies, but due to their small fall velocities and cross-sectional areas, the rates of collision amongst droplets of such a small size is very small. Thus, it is still thought that a few large droplets ($r > 20$ μm) must form in a cloud in order to initiate significant growth rates through the relatively random collisions among small, comparably sized droplets. This initial phase of collision and coalescence has been modeled as a stochastic process (Telford, 1955; Gillespie, 1972), or what is now referred to as a quasi-stochastic process (Berry, 1967).

Since condensation theory for a smooth, unmixed updraft predicts a narrowing of the droplet spectrum with time (Howell, 1949; Mordy, 1959; Neiburger and Chien, 1960; Fitzgerald, 1974), the search continues to explain sufficient broadening of the initial distribution to sustain vigorous collision and coalescence growth of precipitation. One school of thought pursued by a number of Russian and Chinese researchers (Beliaev, 1961; Mazin, 1965; Sedunov, 1965; Levin and Sedunov, 1966; Jaw Jeou-Jang, 1966; Wen Ching-Sung, 1966; Stepanov, 1975, 1976) is that small-scale turbulence and associated fluctuations in supersaturation and turbulent mixing may initiate the broadening of the drop-size distribution. Simpler models proposed by Warner (1969), Bartlett and Jonas (1972), and Mason and Jonas (1974) predict only slight broadening of the droplet distribution or produce a droplet distribution of unrealistic shape.

Recently, Manton (1979) developed a more general theory of the interaction of the cloud droplet distribution with a turbulent cloud. The theories proposed by Mazin (1968) and Levin and Sedunov (1966), as well as Warner (1969) and Bartlett and Jonas (1972), represent special cases of Manton's theory. Manton showed that the theories of Mazin (1968) and Levin and Sedunov (1966), which represent supersaturation fluctuations by an eddy diffusivity, initially broaden a narrow droplet distribution in a homogeneous cloud, but that the narrowing of the distribution by condensation eventually overwhelms this tendency. Similar to Warner (1969) and Bartlett and Jonas (1972), Manton also showed that vertical velocity fluctuations cannot of themselves induce broadening of the droplet distribution. This is because variations in time for an air parcel to reach a given level above cloud base are compensated by variations in supersaturation. By assuming that convective cloud turbulence has a high vertical coherence and that fluctuations in the integral radius of the droplet distribution are negatively correlated with vertical velocity, Manton showed that an initial unimodal distribution is transformed into a bimodal distribution at heights above cloud base. The theory predicts that the net dispersion increases with increasing turbulence intensity. The increase in net dispersion is a consequence of the increasing separation of the peaks when the turbulence intensity is large. Consistent with observations, the theory predicts that the dominant mode of the distribution varies slowly as a function of height. Thus the mean droplet radius increases slowly with height, while the dispersion increases monotonically. The theory also predicts that more monomodal droplet distributions will prevail in clouds having low values of the large-scale turbulence intensity. Manton refers to large-scale turbulence as turbulence generated by convective eddies that have high vertical coherence. Small-scale, vertically incoherent turbulence, on the other hand, will tend to attenuate and broaden the distinct modes and will lead to a broad unimodal distribution whenever the large-scale turbulence intensity is low.

Baker *et al.* (1980) also have calculated the effects of turbulence on the initial broadening of a droplet spectrum growing by condensation. In their model, entrainment and mixing are viewed as taking place inhomogeneously. Thus, blobs or streams of unsaturated air mix with nearly saturated blobs, resulting in the complete evaporation of some droplets of all sizes, while others do not change in size. It is thus assumed that the time constant for turbulent mixing is large relative to the time-scale for droplet evaporation. This assumption is consistent with Manton's (1979) large-scale turbulence assumption for which the turbulence correlation time-scale is large compared to the droplet growth time-scale. Calculations with the model demonstrate that the theory predicts a bimodal droplet spectrum similar to observed spectra, and that the dispersion of the spectra increase with height above cloud base. An interesting feature of the theory is that the largest droplets are predicted to grow much faster than predicted with either the adiabatic or homogeneous mixing theories. The authors attribute the more rapid growth of the largest droplets to local values of supersaturation much greater than either of the two latter cases. In the inhomogeneous mixing model, more droplets are completely evaporated, and the newly activated droplets that replace them cannot compete so effectively for the available water vapor. This leads to a local rise in the supersaturation with droplets least affected by the blob of dry air growing faster. Blyth *et al.* (1980) provided circumstantial evidence from observations of mountain clouds that the hypothesized inhomogeneous mixing process and associated droplet spectral broadening is occurring in real clouds. While one may question the details of the inhomogeneous mixing models of Manton (1979) or Baker *et al.* (1980), they have clearly strengthened the case for turbulent mixing as being a major factor in the formation of embryonic precipitation droplets.

An alternate hypothesis is that the aerosol distribution contains a number of giant or ultragiant aerosol particles which can act as the embryos for further coalescence growth. Observations reported by Nelson and Gokhale (1968), Hindman (1975), Johnson (1976), Hobbs *et al.* (1977), and Hobbs *et al.* (1978) have shown the presence of potentially significant concentrations of aerosol particles of sizes as large as 100 μm. Johnson (1979) calculated that these particles are sufficiently numerous to account for rapid development of precipitation-sized particles, even in colloidally stable, continental clouds. Woodcock *et al.* (1971) and Takahashi

(1976), however, have concluded that giant salt nuclei do not contribute substantially to warm rain initiation in maritime clouds.

A resolution of the question—does the aerosol distribution or the magnitude of cloud turbulence ultimately control the formation of embryonic precipitation droplets in clouds? —is essential to the development of a firm foundation to the modification of warm clouds. Otherwise, one can take the skeptic's view as portrayed by Telford and Chai (1980) who claim that "the process which controls the mixing which depends on parameters such as the inversion at cloud top, the humidity of the overlying air, and the virtual temperature profile of the surroundings, are all more likely to be the factors which decide when a substantial cloud does not rain, rather than the presence of large numbers of cloud nuclei, as previously thought."

Once sufficiently large embryonic precipitation droplets are formed, turbulence, electric fields, and drop charges all are thought to influence the rates of drop collision and coalescence. An analysis of the effects of turbulence on droplet collision and coalescence has been performed by de Almeida (1975, 1976). His calculations suggest that a turbulent cloud with dissipation rates of 1 to 10 $cm^2 s^{-3}$ can significantly enhance the collision efficiencies of 15 μm radius collector droplets. Pruppacher and Klett (1978) argue that the effects of turbulence on drop collision is overestimated by de Almeida's model. Moreover, owing to the very small total collection kernels of droplets $r < 20$ μm, the influence of turbulence on collision and coalescence must be very great in order to account for the initiation of precipitation embryos. The effects of drop charge and electric fields on collision and coalescence have been examined both theoretically and experimentally by numerous investigators over the years (Davis, 1964a,b; Sartor, 1960; Davis, 1965; Krasnogorskaya, 1965; Lindblad and Semonin, 1963; Plumlee and Semonin, 1965; and Semonin and Plumlee, 1966). The results of these studies suggest that the collision efficiencies for small, strongly charged drops can be considerably enhanced in field strengths characteristic of thunderstorms. However, Pruppacher and Klett (1978) conclude that weak charges and weak fields that would be expected to be present in developing warm cumuli will probably not significantly promote the initiation of precipitation embryos.

Whatever the nature of the process of initial broadening of the droplet spectrum, the portions of a given cloud most favorable for the initiation of precipitation in warm clouds are the regions of highest liquid water contents (LWC). Twomey (1976) showed that if locally enhanced regions of LWC comprise only 1% of the cloud volume, and exist for periods of a few minutes, such regions can produce significant concentrations of large drops averaged over the entire volume of the cloud. Thus, the presence of protected updrafts having nearly moist adiabatic liquid water contents (Heymsfield *et al.*, 1978) can have significant bearing upon the initiation of precipitation in warm clouds. Of course, the ultimate amount of rainfall from a given cloud is controlled by the overall time-space character of its updrafts and its liquid water contents.

Langmuir (1948) suggested that once raindrops grow to a critical size of ~6 mm in diameter, they will break up, due to hydrodynamic instability. He hypothesized that each breakup fragment will act as a new precipitation embryo, which can grow to breakup size and create more raindrop embryos. He referred to this process as the "chain reaction" theory of warm rain formation. Other observations (Blanchard, 1948; Magarvey and Geldart, 1962; Cotton and Gokhale, 1967; Brazier-Smith *et al.*, 1972; McTaggart-Cowan and List, 1975) have suggested that collisions amongst droplets on the order of 2–3 mm in diameter and smaller can initiate breakup. Computations of the evolution of raindrop spectra reported by Brazier-Smith *et al.* (1973), Young (1975), and Gillespie and List (1976) have indicated the greater importance of collision-induced breakup over spontaneous breakup to the evolution of raindrop spectra. Srivastava (1978) calculated that for rainwater contents ($M \gtrsim 1$ g m^{-3}), collision breakup results in raindrop size distributions that are approximately constant in slope and have an intercept of the distribution function that is proportional to M. Using a numerical cloud model, Farley and Chen (1975) have concluded that a necessary condition for a Langmuir chain reaction to develop is that a cloud must develop sustained updrafts in excess of 10 m s^{-1}.

One must remember that the evolution of the microstructure of a cloud can have important feedbacks on the evolution of the dynamics of a cloud. One of the most direct feedbacks to the dynamics of a warm cloud is through the formation of precipitation and the subsequent redistribution of water mass in the cloud. It easily can be shown (see Cotton, 1975) that condensed water mass contributes to the cloud buoyancy in a negative way. Thus, in a growing cloud, falling precipitation can unload the weight of water from the upper parts of the cloud, thus contributing to an enhancement of the updrafts in the upper part of the cloud. At the same time, if the falling precipitation enters the updraft of the cloud at low levels, the added water loading can retard the inflow into the cloud. Thus, in a weakly sheared environment, it is possible for a greatly accelerated precipitation process to lead to the early termination of the cloud lifetime by virtue of quenching the cloud inflow. In such a case, more rapid precipitation initiation could lead to less rainfall on the ground. The precipitation process also can lead to the exposure of condensed water to an unsaturated environment. Thus, precipitation falling into a dry subcloud layer will evaporate and cool the air leading to low-level downdrafts. Such low-level downdrafts can have significant bearing upon the subsequent propagation of the cloud system.

In summary, then, the ultimate control on the initiation, evolution, and intensity of rainfall from warm clouds is the time-space structure of a cloud's updraft and LWC. These cloud thermodynamic and dynamic properties, along with the initial activated droplet population, provide the boundary conditions (i.e., time-scales available for particle growth, liquid water available for particle growth) that ultimately determine the intensity and duration of precipitation. In simplest terms, clouds most likely to produce warm rain are maritime and warm-based. The maritime, warm-based cloud has a lower concentration of activated cloud condensation nuclei and, therefore, for a given LWC is more likely to have a broader droplet spectrum (i.e., produce a few big droplets). Furthermore, a warm-based cloud has a larger saturation mixing ratio at cloud base, and therefore its potential for condensing a significant amount of LWC is greater. By con-

trast, a continental, cold-based cloud activates a larger concentration of CCN and has a smaller saturation mixing ratio at cloud base. Thus, the continental, cold-based cloud has a lower liquid water potential, and must distribute its more limited LWC over more droplets, further lowering its potential for creating precipitation. The potential for warm rain formation in most clouds will lie somewhere between these two extremes.

The importance of warm-cloud precipitation processes on the evolution of the ice phase in supercooled clouds has become increasingly evident in recent years. Cotton (1972) noted that the presence of supercooled raindrops greatly facilitated the rapid release of additional latent heat in simulated seeded clouds. Small ice crystals nucleated by deposition or freezing of cloud droplets were rapidly collected by supercooled raindrops, thereby immediately becoming frozen raindrops, or graupel particles. In the absence of supercooled raindrops, an order of magnitude higher concentration of ice crystals had to be nucleated in order to obtain a similar dynamic response in a cloud. Rokicki and Young (1978) and Nelson (1979) further emphasized the importance of warm-cloud precipitation processes to the subsequent evolution of ice-phase precipitation.

Consideration of a rime-splintering process such as the Hallett and Mossop (1974) ice multiplication mechanism introduces an even greater importance of the warm-cloud precipitation process to the evolution of the ice phase. Chisnell and Latham (1976) and Koenig (1977) pointed out that the formation of supercooled rain is important to the rapid development of the advanced stages of riming, and hence, secondary ice particle production. Thus, the warm-cloud precipitation process can not only directly alter the evolution of precipitation in supercooled clouds, but also the dynamic history of the cloud by virtue of the additional latent heat released. The reader should keep these facts in mind when interpreting the results of warm-cloud modification experiments discussed in subsequent sections.

3. Precipitation modification by alteration of the microstructure of warm clouds

In this section, experimental and theoretical investigations of planned and inadvertent modification of the microstructure of warm clouds are reviewed. Included in this section are studies of: a) retardation of cloud condensation nuclei (CCN) growth; b) stimulation of coalescence by electric fields or drop charging; c) water spray seeding; d) hygroscopic particle seeding; and e) ultra-giant particle seeding.

a. Retardation of CCN growth

It was noted in Section 2 that the very high concentrations of CCN in a continental airmass reduces the likelihood of warm rain initiation. This fact has motivated a number of researchers to attempt to develop techniques of "poisoning" the natural aerosol spectrum to retard their activation as CCN. The generally followed approach has been to introduce surface active materials (SAM). Other forms of SAM are thought to promote an increase in coalescence efficiency, and increase the probability of breakup. In the latter case, this could presumably initiate the Langmuir-chain reaction mechanism. Podzimek and Saad (1975), and Podzimek (1979) have reviewed the recent status of cloud modification by introduction of SAM. Much of the field-related work has been aimed at the modification of fogs with generally inconclusive results. Laboratory studies and numerical models have indicated certain types of SAM can be effective in retarding the activation of CCN and condensational growth of droplets. Podzimek (1979) has recommended, however, that further laboratory and numerical modeling studies be conducted before any large-scale field experiments are performed.

b. Stimulation of coalescence by electric fields or drop charging

Lord Rayleigh (1879) first suggested a possible connection between rain formation and electrical effects. Cochet (1952) concluded that charged water drops could accelerate the collision and coalescence process. Numerous laboratory studies (Sartor, 1954; Goyer *et al.*, 1960; Abbott, 1975; Dayan and Gallily, 1975; and Smith, 1972) and modeling studies (Sartor, 1960; Lindblad and Semonin, 1963; Plumlee and Semonin, 1965; Schlamp *et al.*, 1976) have demonstrated that charged droplets and electric fields can significantly enhance collection efficiencies. In these studies, the effect is most pronounced for the smallest collector droplets and for droplets of comparable size that exhibit little difference in relative momentum. The electric field strengths producing the greatest effect have magnitudes of the order of those found in thunderstorm and pre-thunderstorm conditions. Most of the more recent investigations of artificially imposed drop charge or electric fields have been aimed at increasing fog visibility by enhancing coalescence. Tag (1976) concluded that unrealistically large field strengths combined with specific fog spectra are required for a noticeable improvement in visibility. One must be cautious, however, in extrapolating Tag's (1976, 1977) pessimistic conclusions to the more collision- and coalescence-favorable environment of cumulus clouds. Nonetheless, the logistical problems of performing substantial modification of drop charges or electric fields in cumulus clouds leads me to conclude that this is not a feasible approach to the modification of warm rain.

c. Water drop seeding

Braham *et al.* (1957) reported on the results of seeding maritime, tropical (warm-based) cumulus clouds with a spray of water. The experimental design was an outgrowth of Langmuir's (1948) chain reaction theory in which he (Langmuir) suggested that seeding a cloud with water drops could initiate the chain reaction mechanism. He even suggested that water drop seeding could be just as effective as seeding supercooled clouds with dry ice.

Coons *et al.* (1949) and Bowen (1952) carried out limited exploratory experiments in water spray seeding. Bowen (1950) and Ludlam (1951) carried out model calculations of water spray seeding. They suggested that seeding at cloud base height with a spray of 20–30 μm droplets would produce the optimum effects.

Braham *et al.* (1957) released a water spray in maritime tropical, tradewind cumulus clouds in the Caribbean a kilometer or so above cloud base. In contrast to Bowen (1952),

they preferred to seed at levels above cloud base height. They argued that cloud base seeding requires a more optimum sizing and numbers of spray droplets in order to produce the greatest effect. That is, too small a seed droplet may not have large enough collection kernels for rapid growth, and too large a seed droplet may have too shallow a trajectory through the cloud for optimum growth. This decision was probably a valid one for the time, since the technology was not available to them for producing optimum-sized droplets. Furthermore, the optimum size of droplets depends on the liquid water content and updraft structure of a cloud; this information that was not readily available to them.

The greatest response to seeding was observed by Braham *et al.* (1957), when the clouds were seeded at a rate of 450 gallons of water per mile. It was observed that the average time required for precipitation initiation in seeded clouds was 6 min less than in untreated clouds. Furthermore, of 46 randomized pairs of selected clouds seeded at the rate of 450 gal./mi, 11 unseeded and 22 seeded clouds produced radar echoes.

These experiments produced convincing evidence that water spray seeding does enhance the rate of formation of precipitation. Braham *et al.* (1957) concluded that water spray seeding can increase the amount of precipitation on the ground. Certainly, a more rapid initiation of precipitation will enhance precipitation from clouds that would not otherwise produce rain. They argued, however, that because the behavior of observed radar echoes in untreated and treated clouds is similar, the treated clouds produce more rain on the ground. This argument is not very convincing to this reviewer, however.

Because large quantities of water must be carried aloft by aircraft, this technique of rainfall enhancement has not been viewed as an economically attractive proposition.

Recently, Rokicki and Young (1978) performed numerical simulations of water drop seeding in a Lagrangian parcel model. They introduced a spray of seed droplets at cloud base whose size was selected so that their fall velocity did not exceed one-tenth of the updraft velocity. Seed drop radii ranged from 60 μm to 200 μm. The clouds they simulated became supercooled, thus alterations in the warm-cloud microstructure affected the ice phase evolution (see Section 2). In their analysis, a seeding effect was evaluated on the basis of the time required to initiate precipitation. They concluded that water spray seeding should be considered for precipitation enhancement in mid-latitudes as well as in the tropics. They also concluded that its effect is generally greater than AgI seeding with no danger of overseeding. The large collection drops would "short circuit" the need for ice crystals to grow and become collectors. Here again, the importance of warm-cloud modification to the evolution of precipitation in supercooled clouds is emphasized.

d. Hygroscopic seeding

By far the most popular technique for attempting to modify precipitation from warm clouds has been to introduce hygroscopic particles into the cloud. Under the assumption that giant hygroscopic nuclei play an important role in initiating the collision and coalescence process in natural clouds, investigators have seeded clouds with dry salt particles ranging in size from 5 to 100 μm or greater. The popularity of the approach is derived from the fact that dry salt particles of diameter ~10 μm will grow rapidly in size, once they encounter a supersaturated cloudy environment. After only a few hundred meters rise in a cloud, 100 g of salt would be equivalent to a gallon of water in 50 μm diameter droplets (Mason, 1971). Thus, hygroscopic seeding enjoys a much greater economic potential than water spray seeding. Moreover, several investigators have dispersed salt from ground-based generators (Fournier d'Albe *et al.*, 1955; Fournier d'Albe and Alemán, 1976; Roy *et al.*, 1961; Biswas *et al.*, 1967), a technique hardly amenable to water spray seeding.

A major experiment in salt seeding was carried out in northwestern India (Roy *et al.*, 1961; Biswas *et al.*, 1967; Murty and Biswas, 1968). The experiment was carried out during the monsoon months of July to September, when the predominant clouds were cumuloform. A well designed, randomized seeding experiment was conducted in three regions in the plains of India (Delhi, Agra, and Jaipur). Seeding was accomplished either by spraying from the ground a dilute salt solution using power sprayers and air compressors, or by dusting a finely powdered salt and soapstone mixture. The estimated dispersal rate at the source was approximately 2×10^{10}, 5 μm radius salt particles per second. Days on which rain occurred frequently or continuously during the mid-day period were suspended as seeding days. They argued that warm-cloud seeding was not applicable under such conditions.

The results of the statistical analysis of the experiment suggested that a 41.9% increase in rainfall occurred on seed days in the downwind direction. It is fair to say that such a large increase in rainfall exceeded the expectations of even the most optimistic proponents of warm-cloud modification! In view of the magnitude of these results, it is surprising to this reviewer that this experiment has not undergone thorough, independent reanalysis in the reviewed literature.

Personal discussions about the Indian experiments with a number of scientists in the cloud physics/weather modification community reveal that few scientists accept the results as being scientifically credible. Mason (1971) has verbalized this skepticism by pointing out that "the number of salt particles injected into the clouds cannot have been sufficient to produce a detectable amount of rain even if each grew into a large raindrop." Simpson and Dennis (1972) have suggested that "the inferred 'positive results' that arose might have occurred because of variations in rainfall in the *upwind control areas and are not necessarily attributable to downwind seeding increase.*" Warner (1973), however, could not find any significant bias in the statistical design of the experiments. Nevertheless, he does not regard the experiments as convincing for three main reasons:

1) what evidence exists suggests that the natural background of giant hygroscopic particles was of the same order as, and may well have exceeded, that produced by the ground generators—assuming the latter to be distributed uniformly over the whole downwind sector;
2) to account for the 40% increase in rainfall, *every* salt particle emitted from the ground generators would have had to be carried into the clouds and

to grow to a raindrop of 2.1 mm diameter. If only 50% of the particles had been active, they would all have had to grow to drops of 2.7 mm diameter;

3) radar evidence obtained during two monsoon seasons suggests that only 2% of the rainfall was solely due to the coalescence process. In half the remainder of the rainfall, the ice phase was clearly involved and in the other half, the clouds penetrated well above the freezing level and the ice phase was probably involved.

It should be noted that Warner's second comment ignores the possibility that a chain reaction may have developed in the seeded clouds. Clearly, the biggest problem with the Indian experiment is the lack of documentation of any cause and effect. The Indian experiments, therefore, demonstrate that before a majority of the scientific community can view this or any similar experiment as conclusive, the following must be documented in conjunction with the operation of a well-designed randomized experiment:

1) the aerosol distribution immediately below seeded clouds differs from background;
2) the droplet-size distribution in seeded clouds differs from natural clouds;
3) the radar first echo height and echo morphology differs from background.

Analysis of radar echoes for the Delhi region during the experiment has been reported by Chatterjee *et al.* (1969). The results of the analysis of radar echo areal coverage were consistent with the surface rain gage analysis, providing an overall positive effect for seeding for the five-year period. The results also suggested that the seeding effect extended well beyond the surface rain gage network. The echo height analysis, however, indicated that seeded clouds had somewhat lower heights than unseeded clouds. This result seems to be consistent with the hypothesis that hygroscopic seeding lowers first echo heights. It is not obvious, however, that hygroscopic seeding should lower the maximum echo height. The results also suggest that the "luck of the draw" did not favor the unseeded cloud population by introducing deeper, heavier raining clouds in the seeded cloud population.

Subsequent salt seeding experiments in India, either ground-based or airborne, generally produced positive results from seeding, but none of the results were statistically significant (Pillai *et al.*, 1981; Chatterjee *et al.*, 1978), nor was the estimated rainfall enhancement as large as in the earlier experiment. Observational studies associated with aircraft hygroscopic seeding experiments in India (Kapoor *et al.*, 1976; Ramachandra Murty *et al.*, 1975; Khemani *et al.*, 1981) suggest that changes in the cloud droplet distribution, cloud electric field intensity, and cloud chemistry occur as a consequence of seeding. Unfortunately, since these subsequent experiments were not conducted with the same cloud population as the earlier, ground-based salt seeding experiments, they do not *directly* strengthen those results.

While the results of the Indian experiments must still be viewed as ambiguous, they cannot be thrown out as invalid. It is interesting that Warner suggests that the majority of rainfall in the Indian experiment involved the ice phase. In view of our earlier discussions, one cannot rule out the possibility that the Indian salt seeding experiment did, in fact, speed up the evolution of the warm cloud precipitation process, which, in turn, enhanced the conversion of the cloud into ice phase precipitation. Dynamic effects seem unlikely, however, since, at least in Delhi, the radar echo tops were, in general, lower on seed days than on no-seed days. The radar studies mentioned previously do indicate that most of the radar echoes penetrated through the melting level.

Fournier d'Albe and Aleman (1976) reported on a randomized, ground-based salt seeding experiment in Mexico. They dispersed salt at the rate of 50 kg/h during hours of maximum convectivity activity during the summer. Salt particle masses were estimated to range from 10^{-10} g to 10^{-8} g. In all, 54 days were seeded, while only 22 days were used as control days. Their analysis showed that there was significantly less rainfall on seeded days than on control days, relative to the norm. They suggested that their result may have been due to exceptionally heavy natural rainfall on the limited number of control days, rather than a decrease due to seeding. As with the early Indian experiments, no supporting physical observations were obtained in order to assess a possible cause and effect.

Biswas and Dennis (1971) and Dennis and Koscielski (1972) reported on a set of randomized hygroscopic seeding experiments in the state of South Dakota in the United States. Biswas and Dennis described a case study cloud which they claimed "clearly demonstrated that the introduction of proper size rain embryos at cloud base can sometimes initiate the Langmuir chain reaction of precipitation growth." However, Havens (1972) was not so convinced since he assessed that the cloud tops were at −10°C, and AgI seeding also had been conducted in the local region. Blanchard (1972) also was unconvinced that the seeded rain embryos could have grown to breakup dimensions in a cloud of only 3 km depth. In their reply, Biswas and Dennis (1972) performed calculations to show that embryos inserted at cloud base of 100 μm in diameter or greater have a good chance of growing to breakup size (they chose $D > 5$ mm as breakup threshold) and descending through the cloud depth. Based on our discussion in Section 2, a 5 mm diameter threshold for breakup would be very conservative. Perhaps motivated by the above-discussed controversy, Farley and Chen (1975) performed numerical model calculations in which they concluded that for seeding to be effective in stimulating the warm rain process, there must be a mechanism for drop breakup; that for a chain reaction to develop, vertical velocities greater than 10 m s^{-1} are required; and that salt seeding acts primarily to initiate a Langmuir-type chain reaction.

Klazura and Todd (1978) also performed numerical simulations of the salt-seeding experiments in South Dakota. They used a one-dimensional, steady-state, adiabatic, condensation-coalescence model to simulate hygroscopic seeding. They concluded that: 1) for weak updrafts, larger hygroscopic seed particles travel through a lower trajectory and sweep out less water than small, seeded particles. The smaller seeded particles are more likely to grow large enough to break up and create additional raindrop embryos. 2) For strong updrafts, the larger hygroscopic seeded particles grow into precipitation and have a better chance of breaking up and initiating the Langmuir chain reaction, while smaller

particles are not able to initiate precipitation before evaporating at cloud top.

The results of the statistical analysis of 16 randomized salt-seeding cases was reported by Dennis and Koscielski (1972). They found that the average first-echo height for the salt-seeded cases was 1.6 km, while it was 3.4 km for the unseeded cases. An assessment of whether or not a lowering of first-echo height implies an enhancement of rainfall on the ground was not made, however.

Recently, Johnson (1980b) performed a series of salt seeding cloud simulations. A unique feature of Johnson's calculations is that he considered that the natural cloud contained a broad size distribution of nuclei, including numerous particles greater than a few tens of micrometers (see Section 2 for observations of "ultra-giant" nuclei). Johnson claims that these large particles, even if insoluble, can play an important role in initiating precipitation, and the exclusion of this natural background of giant and ultragiant particles can make model calculations unrealistically sensitive to salt particle or large drop seeding. Using such background aerosol distributions, Johnson found that very large salt concentrations of the order of 10^{-3} g m^{-3} were needed to predict rainfall initiation faster than background. This concentration should be compared to Rokicki and Young (1978), who predicted that $\sim 4 \times 10^{-7}$ g m^{-3} of salt could lower first-echo height by about 1700 m. Johnson basically concluded that "clouds with naturally inefficient warm rain processes will still be inefficient after seeding." He also noted that "hygroscopic seeding is not a magic wand that will change the nature of the seeded cloud, but rather a crowbar that can force changes if applied with sufficient vigor." Combining Johnson's conclusions with Takahashi's (1976) conclusion that naturally occurring giant salt nuclei do not contribute substantially to warm rain initiation in maritime clouds, one can conclude that those clouds with warm rain processes that are very naturally efficient are not likely to be significantly affected by hygroscopic seeding.

e. Delivery of hygroscopic seeding materials

It should be mentioned that the delivery of hygroscopic materials, such as salt, is not a trivial matter. It is difficult to grind sodium chloride (or a similar salt) to a desired and controlled size spectrum and to prevent the particles from clumping together. Sprays of mixtures of urea and ammonium nitrate have been used, but according to Silverman and Kunkel (1970), they offer little advantage over ground salt. Salt is also extremely corrosive. I have flown in a one-year-old aircraft that had been used for salt seeding. The aircraft was on its second set of control cables and virtually none of the avionics was operable. Nelson and Silverman (1972) reported on the use of microencapsulated urea for warm fog dissipation. The technique eliminates most of the handling and dispersion problems associated with standard salt and provides a means of very accurate sizing of the particle spectrum. Presumably, the technique should be quite suitable for hygroscopic seeding of warm clouds.

f. Indications of inadvertent modification of aerosol distributions and rainfall

Before I leave the subject of hygroscopic seeding, I would like to review some of the studies of inadvertent modification of clouds with the hope of better establishing a causal-effect relationship between modified aerosol distributions and rain on the ground.

Hobbs *et al.* (1970) have reported on particularly large increases in mean annual precipitation (over 30% in some cases) adjacent to or downwind of some larger industrial sources of CCN in the state of Washington. Precipitation anomalies were inferred from stream flow records. They postulated that the plumes from paper mills contain both higher than normal concentrations of CCN and large particles ≥ 0.2 μm. Subsequent studies (Eagen *et al.*, 1974; Hindman *et al.*, 1977a,b) revealed that the paper mill plumes contained higher concentrations of large (0.2–2 μm diameter) and giant (>2 μm diameter) CCN, but no significant change in small CCN (<0.2 μm diameter). Moreover, cumulus clouds located in the plume contained higher concentrations of large droplets (≥ 30 m), but similar concentrations of droplets ≥ 5 μm diameter as clouds outside the plume.

This study is interesting because in a region of an inferred significant precipitation anomaly, they observed a well-defined anomaly in the aerosol distribution and in the cloud droplet distribution, the aerosol/droplet anomalies being in favor of an enhanced warm-rain process. However, Hindman *et al.* (1977c), using the observed aerosol/cloud droplet distributions as input into a one-dimensional cumulus model and a stratus cloud model, revealed that the large and giant CCN emitted by the paper mills are unlikely by themselves to be responsible for the observed 30% increase in precipitation near the paper mills. Hindman (1976) suggested that the dynamical processes in warm cumulus clouds may be invigorated by heat and moisture released from a paper mill. This invigoration, in conjunction with the acceleration of warm cloud precipitation processes by additional large and giant CCN from the mill, provides a potential mechanism for creating the observed rainfall anomaly. I also would like to point out that many of the clouds that contributed to the observed rainfall anomaly were not wholly warm clouds. In fact, many extend deep into supercooled cloud layers. Here again, the possibility exists for a modified warm cloud microstructure to interact with the evolution of precipitation in the ice-phase with the additional potential for dynamic effects.

The METROMEX field experiment offers another possibility of defining a causal link between observed anomalies in the aerosol distribution and rainfall anomalies on the ground. Estimated summer rainfall increases downwind of St. Louis amounted to 25%, and even greater percentage increases in thunderstorms and hail (Changnon *et al.*, 1976). Observations of greater droplet concentrations and narrower droplet distributions in urban and downwind fair weather cumulus, rather than in upwind clouds, led Braham (1974) and Semonin and Changnon (1974) to hypothesize the existence of giant CCN to explain lower first-echo heights in urban areas, rather than rural areas. In the absence of the hypothesized giant CCN, the observed "more continental" urban clouds would be expected to be more colloidally stable, and thus have higher first-echo heights. Support for the giant CCN hypothesis was provided by Johnson (1976), who found that the average downwind total ultragiant (particles >5 μm) particle volume was 1.8 times that of the average upwind volume. Ochs and Semonin (1979) noted that the particles observed by Johnson appeared to be insoluble with a

thin coating of soluble material. Ochs and Semonin (1979) carried out a number of numerical experiments using as input aerosol distributions upwind and downwind of St. Louis. They concluded that variations in CCN concentrations in the small, large, and giant-size ranges did not explain the METROMEX observations of urban-rural first-echo differences. Further examination of urban-rural first-echo differences reported by Ochs and Johnson (1980) support the conclusion that urban-induced dynamic effects were responsible for the observations.

Ochs and Semonin also pointed out that their model was sensitive to the presence of CCN with radii >5 or 10 μm. Complete elimination of these ultragiant particles significantly retarded the formation of precipitation. However, they concluded the observed variations in the concentration of CCN >5 μm radius do not account for the first-echo observations of urban and rural clouds. Thus, while variations in aerosol and cloud droplet distributions were found to be associated with first-echo anomalies and surface rainfall anomalies, a direct causal link has not been established. Again, other factors affecting the dynamics of clouds are likely to be of greater importance. I shall discuss these factors in the next section.

Before we leave the subject of hygroscopic seeding, we should note that anomalies in CCN concentration have been found to be associated with rainfall decreases. Warner and Twomey (1967) found that the smoke from sugar cane fires was a prolific source of CCN, and clouds in the downwind plume were observed to have higher than normal cloud droplet concentrations. Warner (1968) found that a reduction in rainfall at inland stations over eastern Australia coincided with increasing sugar cane production. He could not eliminate the possibility that other climatic factors contributed to the trend, however. Woodcock and Jones (1970) attempted to obtain independent confirmation of Warner's hypothesis that enhanced CCN caused a reduction in rainfall. They analyzed precipitation records over Hawaii in two locations. One location was downwind from a major cane-growing region, while the other was not. Downward trends in rainfall over a 30–60 year period were detected in both areas, but the trends were not statistically significant. They concluded that factors other than sugar cane burning are probably involved in the rainfall trends. Subsequently, Warner (1971) attempted to find independent confirmation of his hypothesis by examining rainfall records in another sugar cane producing region in eastern Australia. That study did not lend further support to his hypothesis either. Thus, while Warner's hypothesis seems to be physically plausible, and support for the validity of the hypothesis has been obtained in one region, independent confirmation of the hypothesis has not been obtained.

This seems to be the present status of hygroscopic seeding. There is a great deal of tantalizing evidence that seeding with giant and ultra-giant hygroscopic particles can result in the more rapid formation of rain and, perhaps, increase rainfall on the ground. However, a well-defined cause and effect relationship between modified aerosol distributions and enhanced surface rainfall has not been established. Dynamic effects, possibly associated with ice-phase interaction with alterations in aerosol/droplet distributions, may be involved in some of the observed precipitation anomalies that have been intentionally or inadvertently caused. In the next section, I shall review the evidence and hypotheses for the dynamic modification of warm clouds.

4. Precipitation modification by altering the dynamics of warm clouds

In this section, I review the hypothesis and evidence for a dynamic modification of warm clouds. It should be noted, however, that this is an area of scientific investigation in its infancy. In this section, I review field experiments, numerical modeling studies, and hypotheses related to people's intentional and unintentional modification of the dynamics of warm clouds.

a. Intentional modification of the dynamics of warm clouds

Woodcock and Spencer (1967) hypothesized that the latent heat of condensation liberated to the atmosphere by the dispersion of NaCl particles in a nearly water-saturated atmosphere would be sufficient to initiate a cumulus cloud. They estimated that the release of 40 mg of NaCl per kilogram of air would raise the air temperature a few tenths of a degree Celsius. Experiments in releasing salt from an aircraft in the warm, moist marine boundary layer near Hawaii where the relative humidity was 80–90% created some small but visible cumulus clouds. Aircraft-measured temperature excesses were on the order of 0.4°C, less than expected temperature anomalies in cumulus clouds having a precipitation potential. The evidence suggests these clouds were actually "haze" clouds, in that the supersaturations generated were not sufficient to force the solution droplets beyond their critical radii.

Murty *et al.* (1975) suggested that the observed rise in cloud temperature, increase in cloud liquid water content, and increase in cloud depth following massive salt seeding were evidence of a dynamic effect of salt seeding. However, since the observations were for only six clouds and the observed temporal variations in seeded cloud properties were not compared with similarly selected natural clouds, one cannot be certain that these temporal variations of cloud properties are not a reflection of natural cloud behavior. While there may be environmental conditions where more vigorous clouds may be created, it appears the amount of seeding material required to cause a significant dynamic effect makes the approach questionable in terms of cost/effectiveness.

Black and Tarmy (1963) have proposed to coat large areas of coastal deserts with asphalt to change the albedo and induce seabreeze-like, mesoscale circulations and vertical motions, which, in turn, could initiate precipitating cumuli. Asphalt-coated surfaces frequently show temperature excesses over surrounding vegetated land as large as 11°C, and sustain a temperature anomaly through a considerable portion of the diurnal cycle. The technique may be worthy of consideration in oil-rich, semi-arid coastal regions, where asphalt is a by-product of the oil processing industry. Three-dimensional numerical models and computers are currently available that could more quantitatively assess the validity of the hypothesis.

Another hypothesis for cloud modification that utilizes the sun's radiation as an energy source is carbon black seeding. This approach has undergone several periods of interest.

In the late 1950s, the Naval Research Laboratory (Van Straten *et al.*, 1958) seeded eight cumulus clouds with carbon dust, each of which was presumed to have dissipated prematurely. Five seeding runs in clear air were followed by the formation of small clouds. Downie (1960) reported on clear air seeding with carbon black that produced no obvious results. Interest in carbon black seeding was renewed by Gray *et al.* (1976). They argued that dispersal of carbon black on the mesoscale (~100–300 km) with a time-scale of application of 1–2 days, would significantly modify mesoscale circulations. The types of mesoscale weather alteration they hypothesized that have potential to warm rainfall enhancement included:

1) rainfall enhancement from extra solar energy absorption in the boundary layer;
2) cirrus cloud generation, with consequent reduction of tropospheric radiation loss; this might be employed to produce cloud cluster growth or intensity increase;
3) cumulonimbus enhancement over selected land regions in need of precipitation when the natural evaporation rates are high.

One might also consider attempting to induce premature breakup of a non-precipitating stratus deck in order to initiate surface heating and the formation of precipitating cumulus clouds.

They estimate that if carbon dust is dispersed in sizes ≤ 0.1 μm, solar energy absorption amounts as high as ~ 185 GJ kg^{-1} (10 h)$^{-1}$. They estimate that a carbon dust cloud of 10% horizontal area coverage could absorb on the order of 200 joules per day depending on latitude, date, weather, and snow-cover conditions. This, they estimate, is enough to warm a 1 km layer of air about 4°C per day. Clearly, this is a very ambitious effort, requiring the outlay of large sums of money for experimental testing. No organization has agreed to fund such an activity up to the present time. However, serious consideration should be given to performing more extensive numerical simulations on the mesoscale to further examine the validity of the concept and also to examine possible negative consequences of carbon black seeding, such as air pollution.

Gray *et al.* (1976) suggested that the earlier carbon black experiments in the late 1950s and 1960s were not successful because:

1) the amounts of carbon dust were too small;
2) dispersing and clumping problems were encountered;
3) the scale of application was too small (generating or intensifying individual cumuli).

Chen and Orville (1977) performed two-dimensional model simulations of carbon dust seeding on the cloud-scale. They found that a 10% area coverage can produce a vertical velocity of ~ 30 cm s^{-1} in 10 min, but that the vertical velocity thereafter decreases rapidly with time. The results were not encouraging for the direct formation of cloud lines by the dispersion of carbon dust in the tropical atmosphere. However, their results were not applicable to the Gray *et al.* (1976) hypothesis, since the simulated seeding was performed on too small a space and time scale.

Another approach to dynamic modification of warm cumulus clouds is the direct release of sensible heat into the atmosphere. The French Météotron experiment (Dessens and Dessens, 1964; Bénech, 1976) is the best example of such an approach. In this system, an array of 105 fuel-oil burners are deployed in a three-armed spiral pattern within a 140 × 140 m square. Temperatures in the plume (Bénech *et al.*, 1980) have been measured to be 60°C at the 30 m level, and 25°C at the 60 m level, with vertical velocities of 7 to 10 m s^{-1} at both levels. The environmental response to the heat source has been observed to vary with weather conditions. Under conditions supporting cumuli, the plume has been observed to rise vertically into a natural cumulus, and both were carried away by the wind. Under stratocumulus conditions, the plume was observed to produce a cloud-free ring around the plume. There is no documented evidence that the plume is associated with any significant precipitation anomaly, however.

b. Evidence for an inadvertent dynamic modification of warm clouds

Cooling towers represent another localized source of man-made energy released to the atmosphere that may help us understand the potential for modifying warm cloud precipitation by, perhaps, judicious siting of power plants in low rainfall locales. One major difference between cooling towers and the Météotron is that approximately 80% of the energy released in cooling towers is in the form of latent heat, rather than sensible heat. There have been some reports of light snowfall downwind of cooling towers (Kramer *et al.*, 1976) and several scientists (i.e., Hanna and Gifford, 1975) have speculated on larger-scale effects. Some preliminary modeling studies reported by Murray and Koenig (1979) indicate that generation of a convective cloud by heat emission from a cooling tower is dependent upon the size and gradient of the density perturbations in the tower plume. Also, the simulated atmospheric effects were greater when all the energy released was in the form of sensible heat, rather than latent heat. Orville *et al.* (1981) came to the same conclusion in their numerical experiments summarized below. It appears that for man-made localized energy releases in the atmosphere of the order of the Météotron or conventional cooling towers, the effects can be expected to be minimal on precipitation.

Orville *et al.* (1981) reported on the effects of much larger energy releases to the atmosphere associated with proposed power parks (centers containing a number of power plants whose total power output is estimated to be ~50 000 MW). They performed two-dimensional cloud simulations using environmental soundings capable of supporting severe weather. They found that power parks create their own convective dynamics, which interact with the flow of the developing storm to produce storms of less, to greatly less, precipitation output. All but one of their simulated power park cases produced less rain and hail. This they attributed to the rapid cloud development in front of the storm associated with the power park energy emissions; this development saps the energy of the storm, leading to early dissipation of the storm system. It should be noted that this intense competition for the available moist static energy between power park clouds and natural clouds could be exaggerated in a two-di-

mensional model. The reservoir of moist static energy available in a two-dimensional model (note: it can only be accessed in two directions) is much less than it is in the three-dimensional atmosphere. Certainly the level of energy emissions to the atmosphere by power parks may have the potential to alter precipitation. Research is called for, in order that land use planning can be accomplished more intelligently—perhaps to the extent that an equivalent magnitude industrial/energy center can be sited in an area where rainfall is a precious commodity, providing a by-product of energy production, namely: more water!

Before leaving the subject of the dynamic modification of warm clouds, I would like to return to a review of the METROMEX studies. When attempting to assess the extent to which people can intentionally modify warm clouds, I think it is wise to consider to what extent do people unintentionally modify weather. When one considers that people's inadvertent activity occurs 24 hours a day, 365 days a year at levels of alterations in the aerosol structure and thermodynamic structure of the atmosphere far greater than intentional modification, the opportunities are much greater of isolating a physical causal/effect relationship. In the case of St. Louis, a 25 to 30% increase in summer rainfall downwind of the city has been inferred. Changnon *et al.* (1976) conclude that this increase is associated with an increased initiation of rain cells over the urban-industrial areas. The greater level of cell initiation appears to be related to:

1) thermodynamic effects leading to more clouds, higher cloud bases, and slightly more in-cloud instability;
2) thermodynamic and mechanical effects that produce confluence zones where clouds and rain initiate;
3) the effect of added giant nuclei from the urban area that leads to a coalescence process that is more vigorous and more frequent in urban clouds than in rural clouds.

As mentioned previously, subsequent studies (Ochs and Semonin, 1979; Johnson, 1979; Ochs and Johnson, 1980) have indicated that the aerosol effects on the urban precipitation anomaly are of secondary importance. Changnon (1976), however, concludes that the major impact of the urban area is that it results in a greater frequency of cell merger. This, he suggests, is because a greater number of urban-induced echoes are created (Huff and Schessman, 1974) and/or because the urban area promotes greater growth in certain cells that have passed over the urban areas, and this increases the likelihood of a merger there or somewhere downwind of the urban area. Since cell merger has been shown to result in enhanced convective activity and greater rain volumes (Simpson *et al.*, 1971, 1980), this seems to be a plausible connection to the observed rainfall anomaly. Thus, it seems likely that the enhanced cell merger activity would be associated with the thermodynamic effects of the urban environment. These, in turn, would be associated with the changes in land-use in the urban environment (i.e., buildings, greater asphalt-covered surfaces, etc.) (see Auer, 1978).

We should not think that people's inadvertent modification of precipitation is limited to urban regions. Schickendanz (1974) has found rainfall increases associated with irrigated regions in the U.S. High Plains. The estimated percent rain increase associated with the irrigation effect varies from 14 to 26% in June, 57 to 91% in July, 15 to 26% in August, and 19 to 35% during summer, depending on the location of the effect and the size of the target area. Schickendanz postulated that a land-sea breeze effect due to temperature gradients on the periphery of the irrigated area may be a causal factor. Since surface moisture is a major factor in the surface energy budget, one would expect irrigated areas to be cooler than nonirrigated regions at mid-day, and warmer than nonirrigated regions in the early morning hours. This should set up off-irrigated-area flow (divergence) during the day and an on-irrigated-area flow (convergence) during the early morning hours. Since mesoscale convergence has been shown to be a major control on convective precipitation (Ulanski and Garstang, 1978; Chen and Orville, 1980; Tripoli and Cotton, 1980), the associated anomalies in mesoscale convergence would be likely contributors to the observed rainfall anomalies.

The dominance of soil moisture content variations (hence, latent heat transport) over changes in surface albedo on predicted mesoscale circulations also has been demonstrated by Mahrer and Pielke (1978). They found that surface moisture completely masked the effects of surface albedo changes in the simulation of land-use changes over the Negev and Sinai desert areas.

While our understanding of the dynamic modification of warm clouds is quite limited at the present, clearly a potential exists for causing major increases in convective rainfall by systematic planning of land use. It is the opinion of the reviewer that we presently have the computer and theoretical technology to thoroughly examine, by numerical experimentation, the relationships between land-use design and convective rainfall.

5. Concluding remarks and recommendations

It is quite evident from the discussions in previous sections that the major problem in establishing the efficacy of warm cloud precipitation enhancement is that randomized field experiments do not clearly establish that an observed precipitation anomaly is physically linked to seeding. We have, therefore, become extremely dependent upon the use of theoretical or numerical prediction models to establish a cause and effect relationship between a treatment and an observed rainfall anomaly. One must be cautious, however, in interpreting the results produced by such models as being representative of the real world. The problem of modeling hygroscopic seeding is especially severe, since accurate resolution of the aerosol/cloud droplet and raindrop distributions must be preserved throughout the entire precipitation cycle (i.e., through rain on the ground). Artificial, numerical spreading of an aerosol/droplet distribution, for example, can destroy the very essence of the simulation that the investigator is attempting to perform. Due to computer limitations, the modeler must make a compromise between performing an accurate, detailed depiction of the evolution of the microstructure of the cloud, and performing an accurate, detailed depiction of the dynamics of the cloud. The evidence presented in preceding sections suggests that the modelers of hygroscopic seeding and its consequences do not have strong justification

for compromising either the details of the microphysics or the details of the cloud dynamics in their model designs. One must also remember that the theories of the initiation and evolution of warm cloud precipitation and of the dynamics of warm clouds (especially their turbulent structure) are by no means complete.

In previous sections, I have presented my view of the present status of warm cloud modification of precipitation. The picture is not entirely bleak, but there are many loose ends that must be tied down.

As far as hygroscopic seeding is concerned, it is recommended that:

1) further studies should be conducted with the data from the Indian salt-seeding experiments. This would serve to strengthen or weaken the results of the experiment and establish the relative contribution of the ice-phase to the observed precipitation;
2) a search should continue for a causal/effect relationship for the observed precipitation anomalies downwind of suspected local industrial sources of hygroscopic particles and downwind of major urban areas, especially in tropical and semi-tropic regions;
3) any future hygroscopic seeding experiments should not only be well-designed statistically, but also contain sufficient physical observations to establish a cause and effect;
4) cloud models should be continually refined to better simulate hygroscopic seeding and be used as stand-alone exploratory tools, as well as be used as major components in the analysis of field experiments.

I have noted that exploratory studies in the dynamic modification of warm clouds are still in their infancy. However, there exists a major potential for dynamic enhancement of warm clouds either by some form of seeding (i.e., carbon black), or by well-designed land-use planning. Some examples where well-designed land-use planning could lead to precipitation enhancement include:

1) location of and distribution of power-generating facilities with their concomitant sensible and latent heat fluxes, so as to optimize the organization of mesoscale systems;
2) location and mapping of new urban areas to optimize the organization of thermally-driven mesoscale systems;
3) location and mapping of irrigation systems to optimize the organization of thermally-driven mesoscale systems;
4) the mapping of grazing lands and crop-types to optimize the organization of thermally-driven mesoscale systems;
5) the construction of "thermal mountains" by coordinated landfills;
6) the mapping of mining or petroleum production wastes to optimize the organization of thermally-driven mesoscale systems;
7) the mapping of forest cutting to organize thermally-driven mesoscale systems.

In each example, the opportunity exists for the formation of both positive and negative precipitation anomalies. Moreover, an enhancement of the vigor of mesoscale systems also can lead to increased severity of convective weather, including tornadoes, hail, strong surface wind gusts, and local flooding. In tropical regions, only the latter two represent a major potential hazard. Therefore, the emphasis, at this state of our knowledge, should be on exploratory theoretical or numerical simulations. These simulations could be done best in the context of observed environment (i.e., soundings, natural mesoscale features, geography, etc.) where there is a strong desire to develop a capability of dynamic enhancement of clouds. In view of the above discussions, I encourage a greater degree of cooperation among scientists studying planned and inadvertent modification of weather. Furthermore, the need is great for more coordinated research administration over the presently fragmented programs supporting planned and inadvertent weather modification.

Before I leave the subject of dynamic modification of warm clouds, we must recognize that even in the tropics, the convective clouds that contribute most to the rainfall are clouds of sufficient depth to involve ice-phase precipitation processes. Thus, application of warm-cloud seeding techniques in such clouds is likely to influence the evolution of precipitation in the supercooled portion of the cloud. Moreover, the opportunity exists for the application of conventional ice-phase seeding techniques to augment the precipitation efficiencies and dynamics of supercooled cumuli.

Finally, I must broach the philosophical point of whether I, as a scientist, should make recommendations to the weather modification practitioner. Clearly, from the scientific vantage point, the hard scientific evidence for beneficial modification of warm cloud precipitation is lacking. However, regardless of my scientific view, the weather modification practitioner, just as the practicing M.D., will proceed beyond the state of scientific knowledge. Again, as with the M.D., the practitioner must be confident that the treatment does not kill the patient (i.e., decrease rainfall where rainfall is desired). I might speculate, then, that any attempt to enhance rainfall by dynamic modification of clouds with our present knowledge has an equal chance to kill the patient as not. Water-spray seeding at above-cloud-base height has little chance of reducing precipitation. As mentioned previously, the cost-effectiveness of the operation is questionable, however. Cloud-base, water-spray seeding has a somewhat higher risk of reducing rainfall by lowering the trajectory of precipitation embryos (if they develop naturally) below optimum levels. Likewise, cloud-base ultragiant particle seeding has a similar risk, but the economic payoff is potentially greater. Any attempt to optimize the seeding payload by using giant hygroscopic particles also would increase the risk of no—or perhaps a negative—effect on rainfall. In the opinion of this reviewer, ground-base hygroscopic seeding has little chance of success, and perhaps a 50/50 chance of decreasing rainfall.

In all locations where warm-cloud precipitation enhancement is desired, a thorough impact analysis of expected rainfall increases should be made. This analysis should include a thorough hydrological, ecological, and economic analysis for the given location.

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announcements[1]

Second International Meeting on Statistical Climatology

The Second International Meeting on Statistical Climatology will be held in (or near) Lisbon, Portugal, 26–30 September 1983. Plans for the conference are being formulated by an International Organizing Committee under the chairmanship of Allan H. Murphy, Oregon State University. It is anticipated that the meeting will be sponsored by several national and international organizations, including both meteorological and statistical societies. The conference will follow the 44th Session of the International Statistical Institute to be held in Madrid, Spain, from 12–22 September 1983. The principal host organization in Portugal is the National Institute of Meteorology and Geophysics. English will be the official language of the meeting.

The scientific program for the meeting will focus on topics related to the application of statistical methods in climatology and the statistical analysis of climate data (the use of statistical methods in short-range weather forecasting will not be treated at this conference). Both invited and contributed papers will be included in the program. Suggestions concerning individuals who should be considered as potential invited speakers are welcomed. The Organizing Committee is specifically seeking papers on the following topics: design of climatological networks; probabilistic and statistical models of climatological data; time series analysis and spectral analysis of climatological data; new techniques in statistical analysis of climatological data; statistical climate prediction; statistical analysis of climate simulation experiments; Bayesian statistics in climatology; statistical methods in climate impact assessment and in applications of climatological data; and value and use of climatological data. A preprint volume containing the invited and contributed papers to be presented at the meeting will be prepared and made available to all conference participants.

Individuals who would like to submit a paper to be considered for inclusion in the conference program should send *two* copies of both a reviewer's abstract and a publication abstract to Allan Murphy at the address below before *26 November 1982*. The reviewer's abstract should be written in an informative manner and should be approximately 400–500 words in length (the decision to accept or reject the paper will be based on this abstract). A short publication abstract not exceeding 125 words in length is also required for possible inclusion in the preprint volume and/or in an abstracts booklet. Contributors will be notified in January 1983 concerning acceptance or rejection of their papers. At that time, authors of papers accepted for presentation at the meeting will be provided with information regarding the preparation of and deadline for their manuscripts.

For further information concerning plans for the meeting and the conference program, please contact: Allan H. Murphy, Department of Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331. tel: (503) 754-4557.

Environmental Education and Information

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[1]Notice of registration deadlines for meetings, workshops, and seminars, deadlines for submittal of abstracts or papers to be presented at meetings, and deadlines for grants, proposals, awards, nominations, and fellowships must be received at least three months before deadline dates. — *News Ed.*