What Weather Modification Needs—A Scientist's View

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ABSTRACT

The scientific and technological aspects of weather modification are addressed, emphasizing the need for physical understanding, sequential development, predictor variables and an interdisciplinary approach.

The experience of the successful experiments in weather modification such as Climax, Israel and Florida single cumuli have shown the importance of two-phase development, namely, exploratory and confirmatory. A decision ladder to screen out unfavorable cases and/or select between treatments must be optimally based on concepts, numerical simulation and measurement. Cooperation between the academic, government and private sectors in these endeavors will optimize use of people and resources. All these steps together should improve the credibility of weather modification in the scientific community and protect against the present fragility suffered by many operational programs.

1. Introduction

Among weather modification's top priority needs, I perceive those listed in Table 1.

2. Credibility gap

Weather modification hangs on a paradox today. I believe that the field encompasses some areas of established successful operations, and is now potentially on the verge of fruitfully expanding its established applications in the coming decade. The paradox I see is that even the ripest opportunities are not being pursued adequately and overpessimistic statements are broadcast just as we stand on the threshold of major advances in the controlled modification of cloud processes.

Regardless of its origin, the main burden to reduce the credibility gap rests with us, namely, those involved in weather modification research and/or operations. If we fail, the consequences can be too costly. For operational modification projects, instability is enhanced without solid support from the scientific community. For meteorology as a whole, public overheated controversy on weather modification gives the entire profession an image of ridiculous bumblers or even charlatans. Most importantly, if we fail to develop a credible science and practice of weather modification, we may miss one of the greatest opportunities ever offered our pro-

TABLE 1. High-priority needs of weather modification.

Item	Need
1	Greater credibility in the scientific community
2	Longer commitments (5–10 years) to projects
3	Pre-programs and subprograms focused upon each step of the underlying physical concepts
4	Stronger, earlier efforts to identify predictors/stratifications
5	State of the art measurement, treatment and delivery systems
6	Closer cooperation between private, government and university sectors
7	Interdisciplinary, environmental approach/resource analysis
8	Exploration of modification concepts other than cloud seeding

Editor's Note: At the Sixth Conference on Inadvertent and Planned Weather Modification, held during October 1977, a group of six papers addressed the question "What Does Weather Modification Need?" Each author represented a different major stakeholder group in weather modification and each attempted to answer for his or her speciality area. These areas included the weather modification research community, the weather modification industry, the federal agencies who support weather modification research and development, the weather insurance industry, economics of weather, and the social-institutional aspects of weather modification. Each author is a recognized national figure in their speciality area.

This and the following five papers were submitted to the *Journal of Applied Meteorology* and all were accepted for publication. They are not the typical presentations of scientific findings found in most journal papers. However, they are relevant to the readers of JAM because they summarize many scientific findings and combine these with knowledge of business, policy and social realities to form an amazingly clear overview of the multifaceted complex problems that have plagued weather modification. Importantly, the papers set forth those solutions needed to resolve these problems.

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fession to serve humanity—for example, by mitigation of water shortages, crop disasters, and destruction of life and property by storms and tropical hurricanes.

How can the credibility of weather modification be increased in the scientific community? To answer this question, we start by a critique of the first 30 years of this young science, including both the perceived successes and perceived failures. It is most useful to critique the successes first. Weather modification currently has some credibility even in the conservative segment of the scientific community. Why? Mainly because there have been four to six successful randomized experiments such as Climax, Israel, Santa Barbara, Florida single cumulus (and perhaps one or two others in the Dakotas and Australia/Tasmania, for example). By a "successful" experiment I mean one in which the main physical concepts have been confirmed by measurements *and* the treatment/control differences are statistically significant. Although the various august committee reports and some well-planned nonrandomized operations may have contributed slightly, I contend that without these experiments, weather modification would have very little credibility in the scientific community today, nor would there exist so many ongoing operational programs over the world, particularly of the more scientifically sound and therefore usually more expensive variety. The successful experiments share three outstanding features, namely, persistence through at least two phases, often requiring more than a decade; some type of predictive tool or stratification; and a relatively uncomplicated cloud and/or evaluation situation, such as provided by winter continental orographic clouds or by strong target-control correlations. If bluntly honest, we should also admit an element of luck; the successes to some degree "lucked in" to tractable situations, while the failures usually attacked more difficult situations, often those presented by summertime convection.

It is my belief that if the priority items 2–7 listed in Table 1 are implemented, the credibility of weather modification will rise to a viable level in the scientific community.

3. Implementation

The pleas "more resources" and "more research" have usually been cries in the wilderness. The two main factors that bring more resources to weather modification are 1) perceived successes (sometimes those in "rival" nations) and 2) weather disasters, such as drought, hurricane rampages and crop devastations by hail. We must show more successes within existing resources, while at the same time specifically preparing "disaster plans" which comprise good experimental design ready on short notice. Implementation of item 6 in Table 1 could go a long way toward achieving more successes without a major increase in resources.

My intent in item 6 is that closer direct cooperation should be provided to private operations by the government and university sectors to i) permit more measurements before and during modification programs and ii) upgrade evaluation capabilities. We rarely take advantage of the experience, knowledge and facilities acquired by the private sector, which could advance the science and credibility of weather modification without a major increase in total resources.

In my world travels reviewing weather modification projects, I have been impressed by the expertise and up-to-date facilities in use in several private customer-supported projects. A particularly heartbreaking example exists in one foreign country with an excellently run private project. The customers can neither afford randomization nor measuring systems adequate for confident evaluation. Only 100 mi away, the country's government maintains a beautiful radar-surveyed dense surface network in a research mode, while 250 mi in the opposite direction, another government bureau has lavishly equipped a cloud modification project which languishes because of lack of trained personnel! As a beginning cooperation two universities have sent students to participate in and prepare dissertations from analyses of the commercial project and at the end of 1977 the National Water Resources Board agreed to fund cloud physics instrumentation for project aircraft. The additional costs to randomize its seeding on a 3:1 basis would be about 20% of the present budget (less than $1 million annually) while significant advances in concept testing by measurements would only require another 20–50%.

In our country, the Santa Barbara experiment (Elliott *et al.*, 1971) stands as the lone pioneering example of government support and participation enabling a well-designed private project to demonstrate success. In the early phase, a university statistics group helped in the experiment design, a desirable goal for future projects to emulate for their duration (including before and after). The Santa Barbara project also pioneered in the identification of positive downwind effects on precipitation. I regard this downwind positive identification (now in at least three projects) as one of the highest impact advances in weather modification, since it should help allay fears that B must necessarily lose rain if A gains from a treatment effect.

Foreseeable federal resources will only permit two to three simultaneous major government-sponsored, strongly-instrumented, long-term weather modification experiments. These would benefit from private sector experience, via collocation, contracting or other means. They would also vastly benefit from increased university participation, both by students and senior persons. The National Academy of Sciences (1973) recommendation for Weather Modification Statistics Centers has not yet been implemented. Several universities have the nucleus of such groups. Strength-

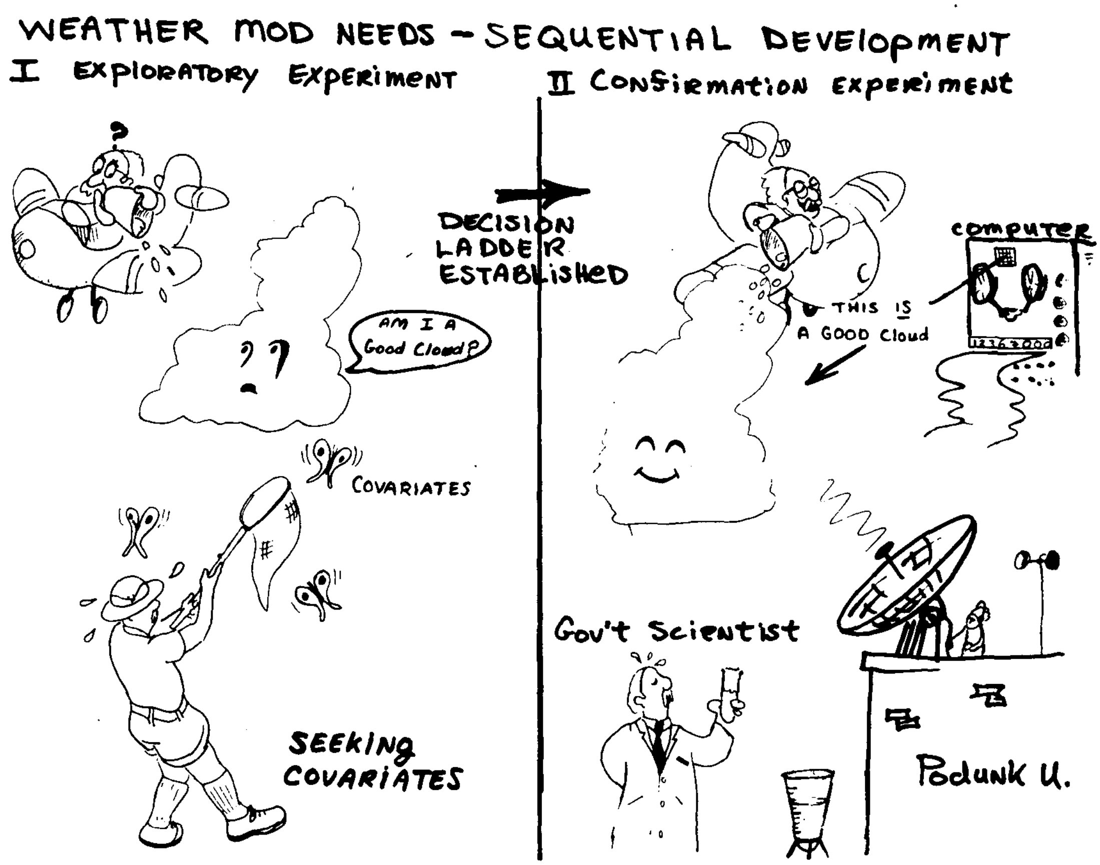

FIG. 1. Diagram illustrating sequential development and intergroup cooperation in weather modification. The exploratory experiment is on the left, showing the quest for screening the cloud conditions suitable for the hypothesis and the search for covariates to reduce the obstacles posed by natural variability. On the right, the confirmatory or "proof of concept" experiment is shown, with models to estimate seedability, radar surveillance and a rain sampling subprogram.

ening these for specific service to ongoing or planned projects could (at relatively small cost) contribute to more efficient design, more effective and more credible evaluation.

A controversial but perhaps productive alternative use of resources would be to eliminate one of the "big-science" projects, applying the freed resourcee to support participation in promising local or private programs where customers are already prepared to supply the basic operation. Building on projects where the inhabitants have already demonstrated a perceived need for weather modification could diminish sociological difficulties, as well as combining resources and talents in a more effective manner.

4. Preprograms and subprograms

Stepwise preprograms are needed to test the applicability of the modifications hypotheses as are tests to insure that the treatment material is properly targeted. Hindsight shows that many of weather modification's failures could have been prevented if we had clearly recognized these needs two decades sooner. In experiments preprograms are also needed when the available data base is not adequate to estimate the distribution of the response variables or when the known variability is so large as to require predictors/stratifications for which the existing data base is inadequate. These preprograms must include estimates of the necessary length of experimentation required to detect a hierarchy of treatment effects at adequate significance levels (Rosenzweig, 1977).

Subprograms are required during an experiment or operation to compare treated and untreated units by measurements (usually many types) to determine whether the treatment is working as hypothesized. Subprograms should also develop and test models or simulations of treated versus untreated situations, evolve new predictor variables, investigate extra-area effects, trace the seeding materials, and investigate the impact of the modification upon the hydrology, water resources, economics, ecology, etc., of the target. Subprograms should also include communications with the customers and/or target inhabitants. Subprograms add to the cost of a weather modification program, but the cost of omitting them is greater, since omission has contributed to the credibility gap. As the various methods of modification become established, most of the attendant subprograms can be phased out.

On the most important lessons learned in weather modification is the necessity of sequential development, with an "exploratory phase" followed by a confirmatory or "proof of concept" phase (Fig. 1).

During the exploratory phase a decision ladder must be established (Fig. 2) which screens out unsuitable days by model and/or measurement and in some cases makes use of stratifications to determine the method of treatment or select the randomization sequence (Brown, 1977).

5. Predictors and stratifications

A main item in Table 1 called for longer commitment to projects. Realistically, we all know that 10-year commitments are rare while many projects apparently just barely fail to achieve significance and credibility because of early termination. The classical approach to obtain statistical significance in the face of high natural variability is to increase the sample size. However, we can all cite programs where either the understanding of the complex processes and/or the experiment design were so poor that a hundred years of unevolving randomized experimentation would

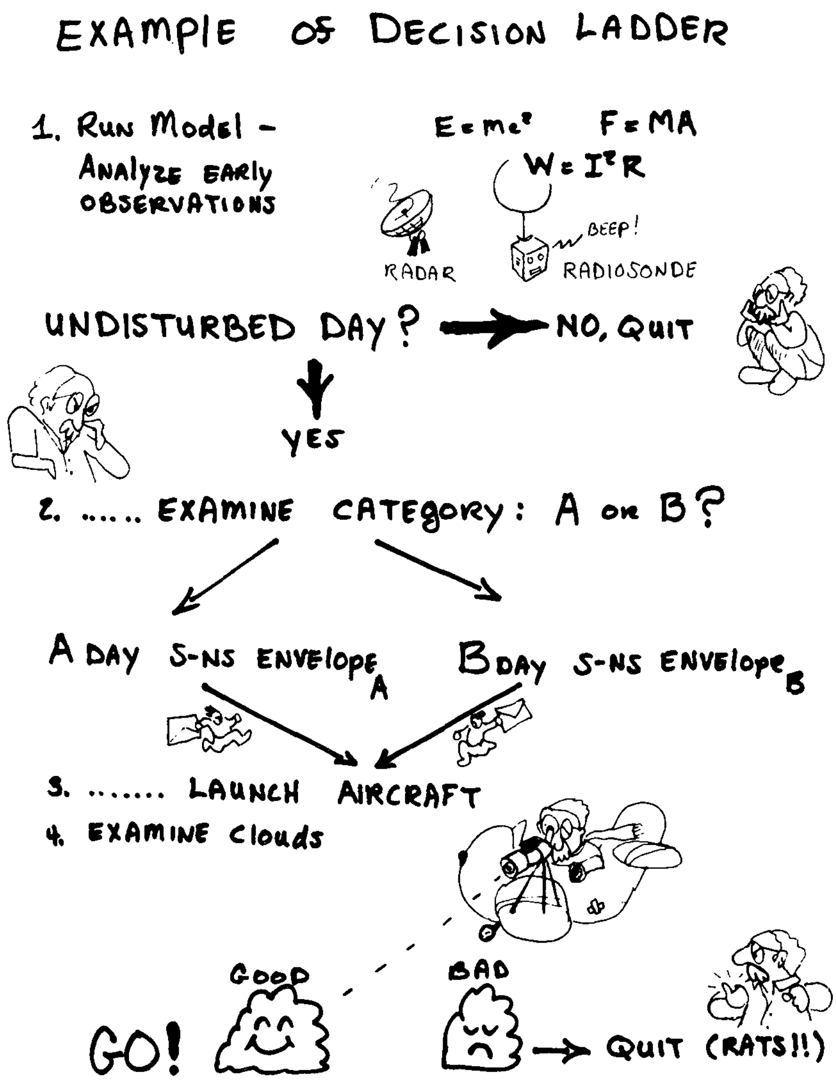

FIG. 2. Illustration of a decision ladder applicable to a seeding experiment. Early morning model runs screen out unsuitable days; examination of these and other data may indicate two types of days (A and B) requiring different treatment levels or possibly involving block randomization so that a different set of "seed" or "no seed" instruction envelopes is opened dependent on this stratification. In this example, aircraft are launched and make prescribed tests of the target clouds before final declaration of an experimental day.

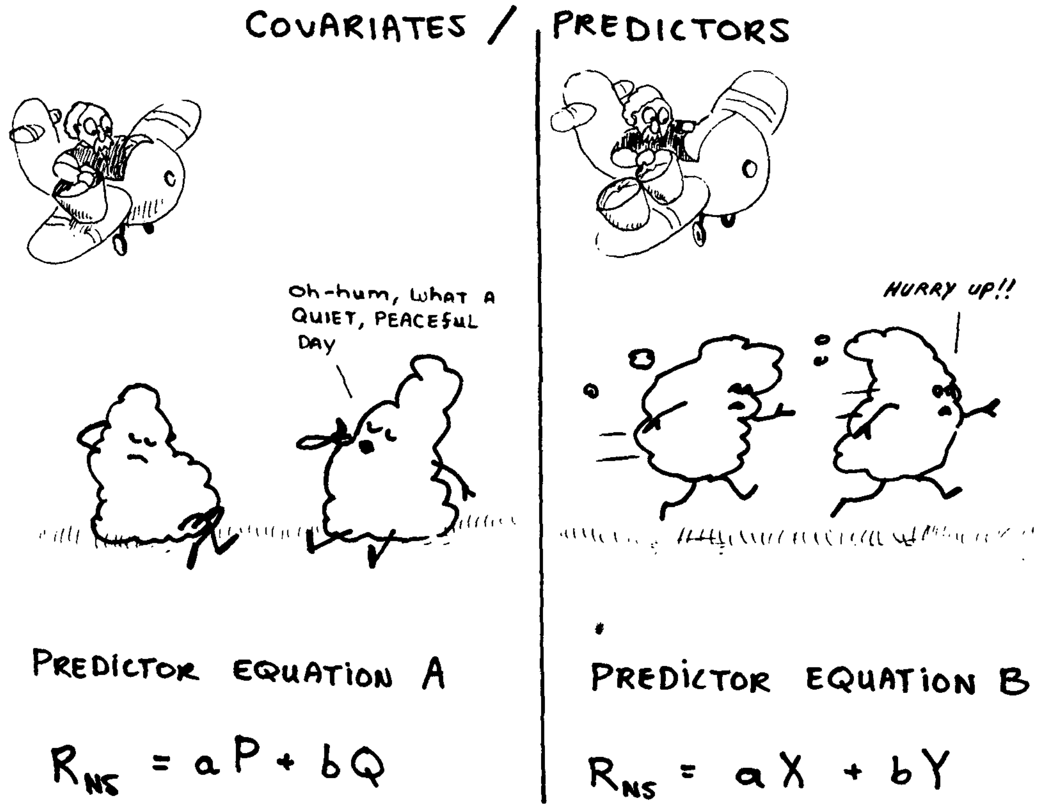

FIG. 3. Illustration of a stratification variable found in the FACE experiment. Both natural rain and cloud response were found to be different depending on whether the target clouds' radar echoes were "marching" or "sitting still." Different predictor equations were evolved with the control data for these echo motion categories.

have produced merely additional inconclusive or uninterpretable statistics. A supplementary alternative which can mitigate the sample size requirement is to make use of information in concomitant variables—i.e., early identification of stratifications, covariates or predictors. Most of the successes in weather modification owe a large part of their achievement to identification of key concomitant variables, either at the outset or after an exploratory phase. In Israel, the correlated rainfall in the unseeded target "predicted," to a degree, what the seeded target would have experienced without seeding; in Florida single cumulus, a simplified numerical model predicted unseeded cloud behavior; while in Climax an exploratory period suggested that cloud-top temperature was a vital stratification variable. A "proof of concept" experiment confirmed both physically and statistically the validity of the stratification.

If convective cloud systems or their products, such as rain, hail or severe weather, are the objectives of modification, natural variability increases relative to fogs and winter storms. Without early identification of concomitant variables, I believe that randomized experimentation or operational evaluation will probably fail. Incorporation of a stratification in experiment design (Brown, 1977) can often make the difference between significant versus inconclusive results in a fixed time limit experiment, or alternatively can save years of expensive experimentation. Furthermore, with some of the skewed distributions characteristic of cumulus variables, Rosenzweig (1977) has shown that doubling the sample size often helps much less in detecting a seeding effect than does the identification of a covariate.

In principle, it is most satisfying if predictor or stratification variables arise either from clearly understood physics, such as cloud-top temperature in Climax (Grant and Mielke, 1967; Chappell *et al.*, 1971) or model simulations based on fundamental equations, as in the dynamic seeding of individual Florida cumuli (Simpson *et al.*, 1967, 1971). Equally useful but less revealing are empirical time and space relationships in rainfall itself, such as target-control correlation, early rain in target correlated to that for "seeding period" etc. (Brier, 1974). It is more puzzling when a stratification such as "echo motion category" in the Florida Area Cumulus Experiment (FACE) (Simpson and Woodley, 1975; Biondini *et al.*, 1977) also presents different effects of seeding (Fig. 3). If this type of stratification continues to be verified statistically, it challenges us to find the reason. The understanding gained should not only improve modification and short-term forecasting in Florida but should relate to the transferability of the FACE approach to other areas and cloud systems.

In weather modification, we cannot afford to reject any means of mitigating the effects of variability by predictors. Every measureable parameter characterizing the environment (on several levels and scales) can be thrown into a stepwise regression or principal component analysis, and those of predictive value selected.

The predictor question strengthens the argument for two-phased experimentation, especially in convective situations. Unless there is an exceptional preexisting data base it will usually require an exploratory experimental period to identify predictors and do "after the fact" stratification. After digesting and interpreting these results, a "proof of concept experiment" logically follows, which can be modeled, measured and analyzed further by subprograms in parallel with the randomized core program.

It should be emphasized that predictors need identification on several scales, in particular, on a pre-experiment basis to screen favorable situations and on a within-experiment scale to direct the treatment to the most susceptible entities to be treated.

6. Systems upgrade

For brevity, this discussion will be focused on systems envisaged for rapid identification of treatable situations and treatment effects, with cognizance of improving remote sensing capability and telemetry.

For example, the best modern aircraft available for weather modification research have on-board computers and visual displays. It is possible for these aircraft to receive the signals from a sounding balloon and a ground network almost simultaneously. On-board, simplified model runs can give such predictions as dynamic seedability and/or hail-size category, for example.

After target clouds have been tentatively identified as suitable, it is crucial to identify as early as possible where seedable (or threatening) entities will grow. Radar pattern recognition adaptation offers a possibility with regard to hail. For rainfall, recent work by Ulanski and Garstang (1977) has shown that a future shower can be identified by a surface "convergence cell" 60–90 min in advance of the appearance of a radar echo. Also the intensity and lifetime of the future shower appears forecastable from the properties of the convergence cell. On-board display of surface winds and, by objective analysis, their convergence fields could guide the seeder to promising areas and keep him away from those where he would be fighting nature. Tri-Doppler radar displays are now available which show the three-dimensional motion field inside a cloud system as it develops. The knowledge gained from the National Hail Research Experiment (NHRE) suggests that for hail supression, the seeding material must be carefully targeted relative to the class of storm and its motion distributions. In FACE, the potential for rain augmentation by dynamic seeding depends on a "seeding" window controlled by the motion field (Sax *et al.*, 1977).

It is recognized that experiments involving sophisticated instrumented aircraft, Doppler radars, telemetering sounding and surface networks, all interconnected by communications to computers, are extremely expensive. Transferability to economic operations will require distillation of the knowledge gained from research experiments into a set of readily measurable parameters introduced into nomograms or readily solved equations.

7. Interdisciplinary environmental approach

On the Arabian peninsula, ultra-dry Qatar and northern Oman receive their scant annual rainfall (6–10 cm) in the same type of Mediterranean cyclones with high static instability (Simpson, 1976). In flat Qatar, there is no runoff to the ocean, no serious risk of flash floods. Five to ten percent of the rainfall recharges the failing ground water; the remainder is lost by evapotranspiration (Pike *et al.*, 1975). In mountainous Oman, nearly one-third of the rain runs off to the sea; there is danger of flash flooding, and the ground water recharge fraction is unknown. Even if the storms in these neighboring areas were equally seedable, seeding would be weighed differently relative to its alternatives if the overall water resources problem is considered. In some developing countries, government structures are still sufficiently flexible to incorporate in one coherent program the feasibility of seeding, the fate of the rain, the hydrogeology, the environmental impacts and the alternative options to compare with weather modification.

In the United States, on the other hand, we sometimes give the impression our job is done when we can state, for example, that "the seeded cases experienced n percent more rainfall than the control cases at the p level of significance." What happens to the added precipitation? How much evaporates, runs off or recharges ground water? Can we seed when clouds are seedable and store the product in snowpack or reservoirs, or must we produce the rain in a short time window dictated by the crop stage, soil moisture, etc.? How many seedable occasions occur during droughts and how different are the physical and economic impacts relative to normal rainfall regimes? In a firefighting situation, far greater demands are placed on weather modification for precipitation. This aspect of weather modification needs a coherent water resource management approach (Fig. 4).

With hail and storm mitigation, the firefighting approach is inevitable; nevertheless the types and impacts of potential modifications cannot be assessed without an interdisciplinary approach. For a particu-

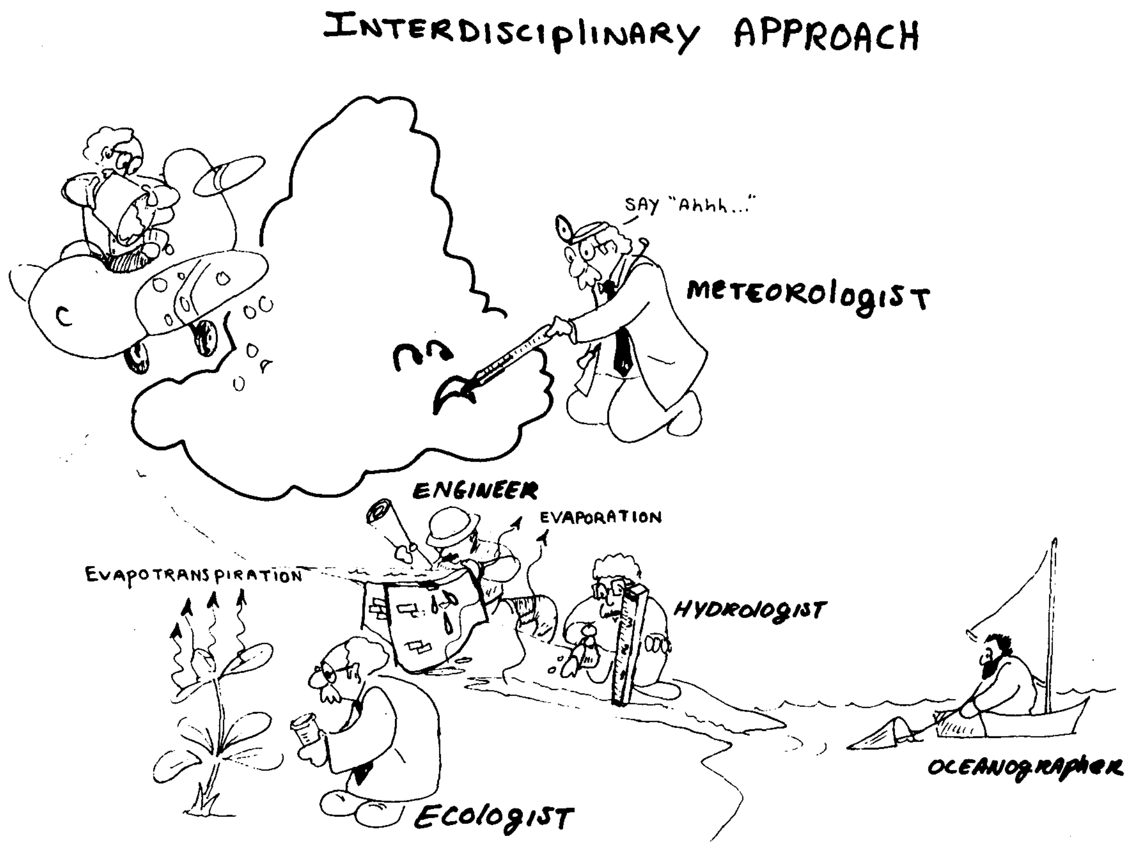

FIG. 4. Illustration of interdisciplinary cooperation in weather modification. An overall "water management" approach is recommended which follows the fate of the rain, its quality and its effects on ecosystems.

larly telling example, a storm surge numerical simulation (Jelesnianski and Taylor, 1973) shows that under some coastal conditions hurricane wind speed reduction accompanied by radially outward migration of the maximum wind could cause a slightly larger not smaller storm surge and thus could possibly increase storm damage rather than reduce it, if the central pressure does not rise.

Moreover, the modification methods of the future may include approaches other than cloud seeding. Most of these will demand knowledge of atmosphere-hydrosphere-ecosphere interactions, with an overall systems resource management approach.

8. Modification approaches other than seeding

Nearly all ongoing weather modification (above the microscale such as smudge pots, etc.) involves cloud seeding.

Some expensive, brute force successes have been obtained by burning fuels to clear fogs or even to create clouds. A more ingenious approach is to use solar heat to alter part of the air-surface boundary or a portion of the free atmosphere. Black and Tarmy (1963) proposed 10 km by 10 km asphalt ground coatings to create a "heat mountain" to enhance rain, or to reduce pollution by breaking through an inversion. Recently, Gray *et al.* (1975) have suggested tapping solar energy with carbon dust over 100–1000 times larger areas for numerous weather modification objectives ranging from rain enhancement, to snow melt, cirrus production and storm modification. The physical hypotheses have undergone preliminary modeling with promising results, while the logistics appear marginally feasible. Drawbacks are the unknown and uncontrollable transport of the dust and its environmental unattractiveness.

A cleaner way of differentially heating the air appears to be a possible future by-product of the space program. A Space Solar Power Laboratory is in the planning stages at NASA. Its main purpose is to provide electric power, which will be achieved by collecting the microwave power sent by the space laboratory to the earth's surface. The microwave power will be converted to dc by means of groups of rectifying antennas, which dissipate a fraction of the power into heat. Preliminary calculations (Pielke, 1976) indicate that the atmospheric effect of the estimated heating would be comparable to that by a suburban area and thus could impact mesoscale processes. Future systems could dissipate much more heat and could conceivably be a clean way to modify weather processes. It is not too soon to begin numerical simulation of atmospheric modifications that later generation systems of this type might be able to achieve.

Radiation alteration appears to be a hopeful weather modification approach still lacking a developed technology. A cirrus cover has long been welcomed as natural frost protection when it restricts the nocturnal loss of longwave radiation. More recently, the effect of cirrus in cutting off shortwave daytime radiation has been modeled and measured (Gannon, 1977). In some cases of heat-maintained convection (e.g., Florida) a cirrus anvil can move or suppress the sea-breeze convergence zones and may be, in fact, the most important feedback of the clouds on their forcing function. Artificial simulation of cirrus effects by minute plastic bubbles impregnated with substances to absorb selected wavelengths received preliminary attention (Simpson and Simpson, 1966) but to my knowledge has not been pursued.

Alteration of the sea-air interface is also a potentially promising weather modification technique, particularly to suppress convection or to mitigate the destruction by tropical hurricanes. The technology in this area could be nearer actual field trials than that in radiation. If methods could be developed to restrict sea-air latent and sensible heat flux, the development from tropical storm to hurricane might be inhibited, while not losing rainfall or other benefits of the system. Presently, the monomolecular films which cut down the evaporation from reservoirs do not stay intact in oceanic storm conditions, even if the logistics of their delivery over wide areas ahead of the storm

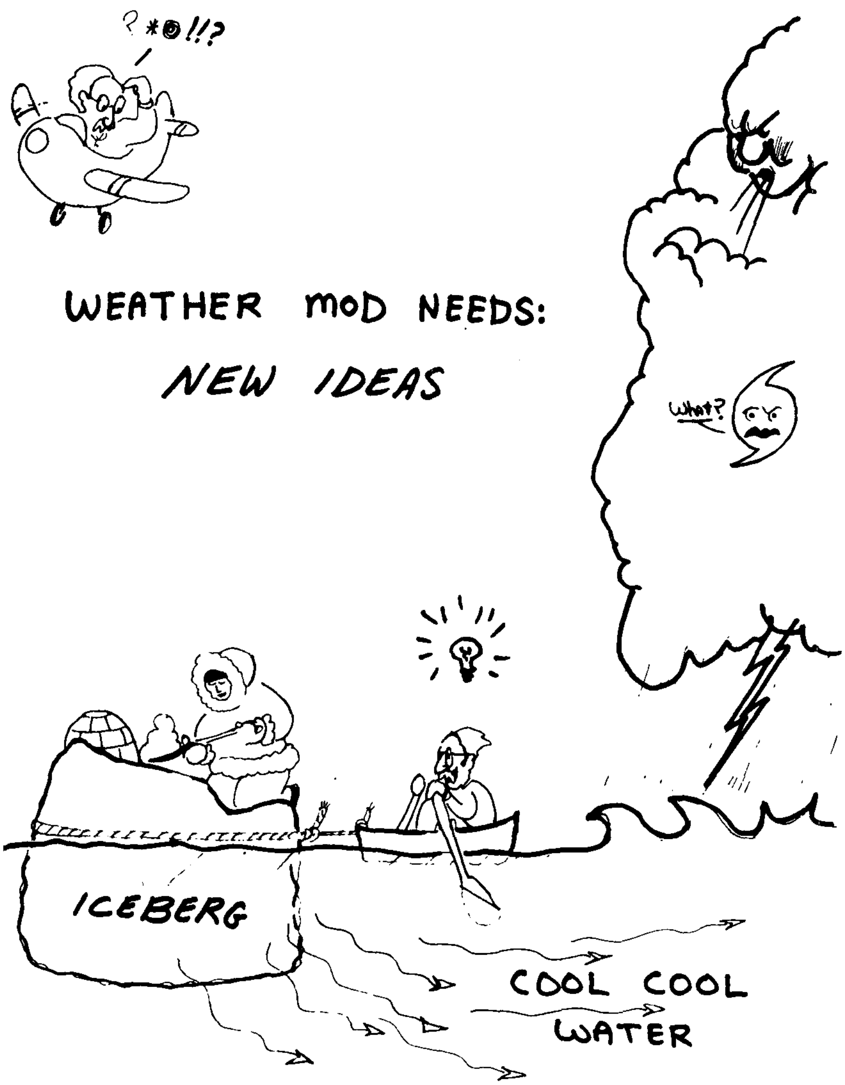

FIG. 5. Illustration of possible new approach to the hurricane mitigation aspect of weather modification. Hurricanes are known to diminish in strength when they move over cooler water, here shown hypothetically to be supplied by a melting iceberg.

were solved. Logistic obstacles have up to now impeded implementation of the promising idea of cooling the waters ahead of the hurricane by mixing up the ocean layer above the thermocline.

However, a combination of promising new technologies under development for other purposes might permit substantial cooling (1–4°C) of the surface waters ahead of an advancing hurricane. The Ocean Thermal Energy Conversion (OTEC) proposes to bring up to the surface quantities of deep cold ocean water in the process of utilizing solar energy. If this water is warmed to a temperature 2–3°C cooler than ambient surface waters, its density deficiency contributed by lower salinity may keep it marginally buoyant. If a greater negative temperature anomaly is desired, the OTEC-produced oxygen could be used to produce a bubble sheet helping to bring cool discharge water continuously to the surface.[2]

Another possibility to cool sea surface waters is presently in the discussion stages. The Arabian government (Simpson, 1978) presently has research underway to tow huge Antarctic icebergs (several square kilometers in area) as sources of fresh water to arid Arabia (Fig. 5). If this technology is successful, possibly some icebergs could be towed and allowed to melt in the vicinity of the OTEC's, to permit the pumped cool water to become brackish enough to remain on the surface even with negative temperature anomalies of 4–6°C.

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