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Weather Modification: Implications of the New Horizons in Research

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For tens of millions of years the development of man and his ancestral stock has been profoundly influenced by the nature of his physical environment. As the species evolved, multiplied, spread over the face of the earth, and achieved mastery of matter and energy, man began to transform the environment in which he was formed and in which he had learned to function. Some transformations are deliberate; others, inadvertent. Some are deemed to be good; others, undesirable. My present concern is with one special way in which ubiquitous man is tinkering with one aspect of his physical environment: with artificially produced changes —deliberate or inadvertent, transient or permanent—in the composition and behavior of the atmosphere.

It is not altogether inappropriate that we turn to this topic at this time. The past year has been an eventful one in the long—and not always happy—history of weather modification, but not because of great scientific or technologic breakthroughs; if any were achieved, they have, I am sorry to say, passed relatively unnoticed as yet. True, it is the 20th anniversary of Schaefer's path-breaking demonstration that supercooled water clouds could be transformed into ice crystals, with some yield of precipitation (*1*). By contrast, the characteristics that made 1966 eventful were cumulative and subtle rather than discontinuous and dramatic; they were nevertheless profound and portentous.

Four developments are worthy of special mention: First, there was general agreement (*2*) that the problem of weather modification was passing from an era of intellectually undisciplined speculation and more or less opportunistic field experimentation into an era of rational, organized inquiry in which a set of meaningful scientific questions could be explored analytically and by means of coordinated and carefully designed field experimentation. The importance of this transformation, and of the fact that it has been identified even as it is underway, cannot be overstated. I am confident that its significance will be even more apparent 100 years from now than it is today.

Second, there was clarification of the efficacy of cloud-seeding intended to augment natural rain or snow. Although couched in the typically—and properly—cautious and carefully chosen words of the panel of the National Academy of Sciences, "There is increasing but still somewhat ambiguous statistical evidence that precipitation from some types of clouds and storm systems can be modestly increased or redistributed by seeding techniques," this conclusion has clearly added new dimensions of practical interest to a problem that was beginning to attract considerable intellectual interest. Keenly aware of the significance of its findings, the panel went on to say, "The implications are manifold and of immediate national concern." Thus the preliminary findings of the Advisory Committee on Weather Control (*3*) of nearly a decade ago have been vindicated, and the controversy in which no one can take a great deal of pride may now be replaced by the positive steps that have been proposed to reduce further the remaining ambiguity.

Third, there was forthright recognition that the implications and issues involved in weather modification transcend the boundaries of the physical sciences and embrace important questions in the social and the life sciences, in international relations, in law and governmental regulation, and in the decision-making structure of the federal government by which it legislates, appropriates, manages, and coordinates national programs that cut across scientific disciplines and departmental missions. These considerations were treated in some detail by a Special Commission of the National Science Foundation (*4*), which clearly stressed the urgent need for detailed analyses of the consequences *before* we are confronted with the task of coping with them.

Fourth, there was the unanimity among the scientific community, the executive branch of the government, and the Congress that a drastically increased research effort (fivefold growth by 1970) in weather modification is required. The speed with which the 89th Congress moved on hearings, studies, and legislation (*5*) leaves little doubt but that the 90th Congress will take definitive action.

Deep issues of science and public policy are involved and it is timely that the dialogue be widened. I welcome this opportunity to widen it; it was the AAAS Committee on Science in the Promotion of Human Welfare that remarked less than 6 years ago (*6*):

> For nearly two decades scientists have viewed with growing concern the troublesome events that have been evoked by the interaction between scientific progress and public affairs. With each increment of power, the problem of directing its use toward beneficial ends becomes more complex, the consequences of failure more disastrous, and the time for decisions more brief. The problem is not new either in the history of human affairs or of science. What is without parallel is its urgency.

I am quite persuaded that these thoughtful words apply today with particular force to the scientific exploration of weather modification. The potential

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increment in mastery over nature, the ever-present hazard that this power may be used as a tool of conflict rather than for the benefit of mankind, and the responsibility to preclude inadvertent initiation of massive irreversible processes that are not in the interests of human life confront our civilization with a complex set of decisions that will be taken—consciously or unconsciously—during the next few decades. Whether the "time for decision" is adequate or inadequate may be debated. That debate, I submit, is irrelevant; the point is that time remains for reflective thought, for setting objectives, and for weighing alternative courses of action —in short, for acting responsibly.

With that thought as a point of departure, let us: (i) examine the scientific problem and the developments that are currently transforming it, (ii) briefly summarize the state of the art, (iii) review the issues, and (iv) close with some of the implications that transcend science.

With respect to the scientific problem, we may think of the atmosphere as a complex physical system in which movement of air, changes in temperature, and transformation of water among the liquid, solid, and gaseous phases are all of considerable practical interest, all taking place in response to certain forces or through particular processes. Although the atmosphere is far from being a tidy little deterministic system, in principle (by altering the forces or interfering with the processes) we can influence the motion of air, changes in temperature, and the phase transformations of water. In this sense, the matter of weather modification is a meaningful scientific problem.

It is, however, a complicated problem. The earth's atmosphere may be viewed as an envelope rotating with the earth as well as relative to it. The relative motion arises because of the forces associated with the rotation of the earth, and forces associated with the sources and sinks of energy that are variable in number, location, and strength. These sources and sinks of energy depend on the distribution of shortwave solar radiation, the flux of outgoing longwave radiation, the latent heat involved in the change in phase of water, the transfer of sensible heat between the atmosphere and the underlying surface, and finally the air motion itself. The kinetic energy of air motion exists in an array of scale sizes that extend from planetary wave systems down to molecular movement. There is continuous exchange of kinetic energy from one scale to another, and the kinetic energy is continually being exchanged with other forms of energy in the atmosphere.

The quantities of energy involved in weather systems and processes occurring naturally in the atmosphere exceed substantially the quantities of energy under the control of man. For example, the energy required for increase of the rainfall by 0.1 inch (2.5 millimeters) over an area 100 miles (160 kilometers) square is equivalent to the sum of the total output of electrical energy in the United States for about 6 days. Thus, even though it is clear that the scientific problem of weather modification is solvable in principle, the outlook would be pessimistic within the foreseeable future were it not for two characteristics of the atmosphere: (i) an intrinsic tendency toward certain instabilities; and (ii) the key role of the processes at the interface between the atmosphere and the underlying surface in determining the energy inputs into the atmosphere.

The attribute of instability is readily apparent, from everyday experience, in the tendency for the amplitude of atmospheric disturbances to increase with time. For example, a small puffy-type cloud may grow to a towering thunderstorm in a matter of hours; a gentle zephyr in tropical latitudes may develop into a "killer" hurricane in a matter of days; and a small low-pressure center may grow to a vigorous extratropical cyclone within a single day.

We are just beginning to understand: (i) the instability of supercooled water droplets which, when released, provide a local source of sensible energy; (ii) the convective instability of a rising current of air within which water vapor is condensing into liquid, thus affecting the vertical distribution of sensible energy; and (iii) the so-called baroclinic instability of the large-scale, planetary atmospheric waves, which when released can profoundly alter the nature of the great global system of winds.

Should it turn out that the upward progression of energy through the size spectrum of instabilities that I cite is a process of considerable significance, an avenue may be opened up by which great effects may be produced from relatively modest but highly selective human interventions. We could, then, break the eggs rather than slay the dragons! Similarly, the sensitivity of the atmosphere to the interplay of the variables that determine the flux of energy, between the atmosphere and the underlying land or water, is beginning to yield to numerical analyses and field measurement. The influence of changing surface parameters such as roughness, reflecting power, and transfer of water across the interface is becoming known, and the possibilities that the effects range beyond a local area are being explored.

Some support for the line of reasoning that links small causes with large effects is found in the results of an examination of fluctuations in the climate that have been either observed or reconstructed from historical or geologic evidence. There is reason to believe that these fluctuations—some of which would be disastrous to modern civilization—may have been caused by the triggering of instabilities by natural processes, through which a given climatic regime was transformed into a radically different one.

There in barest outline is the nature of the scientific problem and the general direction in which it is likely to proceed. The new horizons of research that are suggested by the title of this article arise from four scientific and technological developments:

1) Understanding of the physical processes occurring in the atmosphere has now progressed to the point at which they can be expressed in equations that constitute mathematical models. These models permit simulation of natural processes or—of particular relevance to our topic—assessment of the consequences of human intervention in these natural processes. Although crude and oversimplified relative to the processes they are intended to simulate, useful models have been constructed of atmospheric phenomena that range in size from a single cloud to circulation of air over an entire hemisphere. There is almost unlimited potential for extension and refinement.

2) Development of the modern high-speed computer (which was encouraged initially by the computational needs of meteorological models) has proceeded simultaneously with the growth in sophistication of these atmospheric models, and brings within the realm of reality experimentation by simulation that has hitherto been only a gleam in the eye of the meteorologist. Some of the more difficult problems of nonlinear instability will soon be within reach as the speed and capacity of computers both increase.

3) The third development concerns the expanding capabilities of making

the observations and measurements that specify the initial and final atmospheric conditions that must be reconciled by the computerized atmospheric models if they are to be meaningful. These emerging capabilities range from the use of meteorologic satellites on a global scale to intricate measurements of the relevant physical characteristics of a single cloud.

4) There have been significant advances in the refinement and the power of modern statistical procedures for resolving questions of cause-and-effect relation, in field experimentation, by establishing appropriate "design criteria" for both research and operational projects. The interaction between individuals skilled in these procedures and experimental meteorologists is really only getting underway, but it already promises important contributions to the reduction of ambiguity in the interpretation of weather-modification activities.

Taken together, these four advances set the stage for the rational inquiry into weather modification to which I have referred. Quite clearly, within the next decade or so it will become possible to explore, through simulation techniques, an almost unlimited array of deliberate interventions in natural atmospheric processes, and to assess possibilities and limitations. These studies will inevitably lead to specific requirements for meteorological measurements that will deepen our understanding of natural processes. As an example, mathematical models of the atmosphere have already been used in a preliminary way to assess the consequences of the inadvertent intervention associated with the increase of atmospheric carbon dioxide. Models may yet be used to define the tolerable limits to this large-scale geophysical experiment that mankind is undertaking; or, alternatively, to determine desirable countervailing measures.

As I have already indicated, these scientific considerations take on new dimensions when viewed in the context of the present state of the art. At the risk of oversimplification, this state may be summarized in the following way:

1) Field results have demonstrated unequivocally that several cubic kilometers of clouds, consisting of supercooled water droplets, can be transformed into ice-crystal clouds by seeding with appropriate chemicals.

2) Supercooled ground fog can be cleared from large areas by the same techniques.

3) Persuasive although not conclusive evidence suggests that rainfall can be increased by from 5 to 20 percent (say 10 percent), depending upon the conditions.

4) There are indications that Soviet scientists have succeeded in suppressing hail by introducing silver iodide directly into susceptible parts of hail-producing clouds.

5) Physically reasonable approaches to the suppression of lightning have been tried with mixed but, on balance, promising results.

6) Cloud-seeding techniques that are of sufficient merit to warrant field experimentation have been advanced for the modification of hurricanes, but the limited tests have not yet yielded even preliminary conclusions.

7) No technique for influencing large-scale weather patterns in a deliberate and predictable manner yet exists.

8) With respect to inadvertent weather modification, calculations suggest that the 10- to 15-percent increase since 1900 in the minute amount of carbon dioxide in the atmosphere has caused surface temperatures to rise 0.2°C, while temperatures in the stratosphere may have decreased ten times as much. Air pollution—particularly the ejection of submicroscopic particles of lead from automobile exhaust—may have already extended its influence beyond the urban domain (7). Contamination of the upper atmosphere by rocket exhaust may become a problem of practical importance sooner than we realize. Finally, agricultural cultivation and urbanization are transforming the nature of the surface underlying the atmosphere, with possibly important consequences that we hope soon to be able to assess.

Against this brief background of scientific problem and opportunity, and practical accomplishment as well as frustration, it is appropriate to review the issues now confronting us. To my mind there are two major ones. I stress the fact that each is a very live issue today because the crucial legislative decisions that commit us to a particular course of action have not yet been made.

The first issue is our domestic program—its character, its size, its rate of growth, and its management. Since the character of the domestic program is singly the most important part of this issue, let us examine it. The character of the program should be responsive to the elements involved in the solution of the problem, which include, first, basic research of the kind we designate "little" science: fundamental studies in (i) the physical sciences, engineering, and statistical design theory—nucleation, the physics of precipitation, energy-exchange processes, instability in the atmosphere, sensors and sensing systems, and decision-making in the face of uncertainty; (ii) the life sciences—the ecologic effects of transient or permanent modification of the physical environment of natural biologic communities; biologists warn us that the biologic outcome of modification of the weather is apt to be a "mixed bag" of good and bad effects on man's artificial ecosystems; and (iii) the social sciences—the human effects, including the impact of weather on the individual and on human activity, the "right" of the individual to the weather provided by nature, the gains and losses to different sectors of society that would follow in the wake of atmospheric alterations, assessment of benefits in relation to costs, the likelihood of conflict, and the institutions that may have to be created or transformed to resolve those conflicts.

Second, the elements include applied research of a kind having a specific aim—in which the mission is to develop capability of modifying the weather. This element has all the attributes of "big" science: giant computers simulating atmospheric processes, simulating biologic adaptation to variable ecosystems, and simulating economic input-output models–instrumentation laboratories; extensive field measurement programs and experimental research. This element would close the most conspicuous gap in our present national effort and would give the effort coherence by complementing the current fragmentation that has certain positive attributes.

The third element would be operational application of proven techniques as soon as their efficacy and desirability are established.

The fourth and final element is the regulation that may be required to protect the interests of the public, and the rights, responsibilities, and opportunities of the private sector, as well as to prevent the contamination of field-research projects.

The Weather Modification Act of 1966, passed by the United States Senate last October, goes a surprisingly long way toward development of a domestic program compatible with the elements we have just discussed. Since there was no concurrent action by the

House, the entire matter must be reopened for discussion during 1967 if definitive action is to result.

The second issue is concerned with the manner in which our domestic program interacts with the vigorous national programs in other countries. Basic to this issue is the knowledge that the atmosphere is a single, indivisible, physical system: a large-scale disturbance over one part of the world is reflected in different disturbances over other parts.

Resolution of this issue demands perception and awareness that we are no longer in the 19th century but moving rapidly toward a 21st century in which science and technology will have so transformed society that it will be scarcely recognizable, with science and technology creating new imperatives for foreign policy. Even now the demands on imaginative innovation are so great that they are equaled only by the concomitant opportunities. The international issue demands that we forthrightly recognize the atmosphere, and the benefits it brings, as a resource shared by all nations; recognize that the terrors it holds and the suffering it can cause are adversaries that nations can overcome only through a partnership of effort. If one day we may be able to divert the rivers of rain that course through the skies, let that diversion be for the common good and not for narrow national aggrandizement. The Academy panel stated the case succinctly in these words:

> It is clear that a long-range program of weather control and climate modification can have a direct bearing upon relations between nations. It can aid the economic and social advancement of the less-developed countries, many of which face problems associated with hostile climates and serious imbalances in soil and water resources. And, quite importantly, it can serve to develop common interests among all nations and thus be a stimulus for new patterns of international cooperation.

The NSF commission presented the opportunity in this way:

> Rarely has a more inviting opportunity been offered for advanced thinking and planning regarding the impact of a technological development upon international relations.

The bill passed by the Senate in 1966 included a policy declaration supporting international cooperation and "peaceful and beneficial applications of weather modification."

Now is the time to carry out this policy declaration—while weather modification is still a research problem and *before* there are dramatic demonstrations of capability of large-scale modification. *Now* is the time to take that "long sequence of small, correct decisions" that John von Neumann told us a decade ago would be superior to a "novel cure-all" as a method of resolving the problems attendant on a development that would "merge each nation's affairs with those of every other, more thoroughly than the threat of nuclear war or any other war may have done" (*8*).

The description of plans for the World Weather Watch, discussed at the 1966 meeting of the AAAS, set forth—I hope—one such "small, correct decision." The warm response from our colleagues in other countries stimulates us to rise to the challenge offered by the occasion.

The actions taken by Maryland, in making any form of weather modification a crime, and Pennsylvania, in giving each county the option to outlaw weather modification (*9*), are unmistakable signs of political complication sent out by an "early warning" system to those who would note them. The public concern and indignation in Canada (manifested by 60,000 signatures on a petition requesting governmental intervention), over the *possible* relation between abnormal weather in the Province of Quebec and alleged rain-making activities in the Province of Ontario and in New York State, contain a mild hint of the international complications that could arise (*10*).

In closing let me select, from among the many implications of these new horizons of research in weather modification, three that seem to me to have special significance:

1) There is the suggestion, implicit in what I have said, that the undertaking now just getting started is at such an early stage that it may well be carefully documented as it proceeds and be treated as a case study by scholars concerned with the interaction of science and public policy. All the essential ingredients appear to be present, including: (i) an intrinsically interesting scientific problem, with the outcome uncertain; (ii) a potential for great practical benefits for mankind and an equally great potential for exacerbating man's proclivity for conflict—with moral judgments and the application of ethics likely to determine that outcome; (iii) clear indications of the need for a substantial, specifically aimed program of applied research, with the opportunity to shed some light on the controversial conclusions of the Defense Department's Project Hindsight (*11*) (quite clearly the hazard of inhibiting the emerging and flourishing, undirected, basic research in the atmospheric sciences at several first-rate universities should be avoided); (iv) intricate problems of interdisciplinary interaction among the physical, life, and social sciences; (v) complex interagency coordination and collaboration, with the opportunity for innovation in governmental organization; (vi) involved legal and regulatory questions, as well as issues concerning the role of the private sector; and (vii) an opportunity to integrate emerging scientific and technological elements into imaginative foreign policy. During the decades ahead we must deepen and perfect our understanding of the interaction of science and public policy. The gathering of data on an experiment as it proceeds would be a good start.

2) There is the implication that current and prospective advances in weather modification are placing in our hands what Harlan Cleveland (*12*) refers to as "the technological imperatives" to create or strengthen the institutions for international cooperation that are required to serve the national interests of ourselves and other peoples while simultaneously advancing the welfare of all mankind. Much more than the parochial promotion of a specialized area of science is at stake. Cleveland quotes President Kennedy as remarking that a manageable, worthwhile system of world order will be based "not on a sudden revolution of human nature, but on a gradual evolution in human institutions—on a series of concrete actions and effective agreements which are in the interest of all concerned." If the exploration of weather modification adds one more small brick to the edifice that restrains world conflict and supports world order, science will have served a noble purpose by enriching human life. The burden of responsibility for seeing that this happens is, I believe, on scientists. Long ago Heisenberg underscored the unique role of science in contributing to the solution of one of the great problems of our time with these words (*13*):

> It is especially one feature of science which makes it more than anything else suited for establishing the first strong connection between different cultural traditions. This is the fact that the ultimate decisions about the value of a special scientific work, about what is correct or

wrong in the work, do not depend on any human authority. It may sometimes take many years before one knows the solution of a problem, before one can distinguish between truth and error; but finally the questions will be decided, and the decisions are made not by any group of scientists but by nature itself.

3) Finally there is the implication of an opportunity—nay, necessity—to turn our attention to the structure and the foundations of the moral and ethical framework within which we seek assistance in deciding *why* we must do those things that science tells us *how* to do. What an unparalleled opportunity to synthesize advances toward an understanding of our physical universe with advances in our understanding of man's role in this universe! For, as Teilhard de Chardin has suggested with such simple eloquence in *The Phenomenon of Man*:

How can one fail to recognize this revealing association of technical mastery over environment and inward spiritual concentration as the work of the same great force—the very force that brought us into being.

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Destruction of Molecules by Nuclear Transformations

A molecule may explode as a result of some kinds of nuclear transformation of a constituent atom.

S. Wexler

Picture a molecule isolated in space, one of whose atoms is radioactive, that is, its nucleus is unstable. What happens to the molecule when the particular atom undergoes a nuclear transformation, when it changes to another energy state of the same nucleus or to an entirely different nucleus? For a number of reasons we may expect rather unique molecular effects. First, nuclear transformation is an internal process; the change occurs within the nucleus of a particular atom. The consequences of the nuclear event for the specific atom, as well as for the whole molecule, may be quite different from the effects provoked by an exciting agent, such as an electron, proton, or alpha particle, initially external to the molecule. Since the process takes place in a particular atom, its position in the molecule may be a decisive factor in the effects produced. Then, there are numerous different nuclear processes, and each influences the molecule in a characteristic way.

I will describe some of the phenomena resulting from nuclear transformations occurring in polyatomic molecules (*1*). The primary molecular effects to be discussed are the properties of the product species at the moment of formation, before these properties are altered by collisions of the products with neighboring molecules. The observable properties are the chemical natures, charge states, and kinetic energies of the various fragments formed in the breakup of the molecule. From these measured quantities we may deduce the mechanisms of molecular disruption induced by the nuclear transition. Experimental observations in this scientific discipline are made on an atomic or molecular scale, and they differ from those performed in nuclear physics since the latter usually consider the properties of the lightweight particles and photons initiating the nuclear transitions or emitted in them. The primary molecular processes occurring in nuclear events are studied as part of a general area of scientific interest concerned with the chemical effects of nuclear transformations. Because of the unusual charge, the large electronic, vibrational and rotational energies, and the excessive recoil energies received in the nuclear transformation, the various species, though altered by subsequent collisions, may eventually react chemically with molecules in unique ways not open to the species in their normal states (*2*).

Experimental Techniques

Two requirements must be fulfilled for the decomposition of molecules by nuclear decay to be studied. There must be low pressures of radioactive gaseous molecules to insure that measurements are made on only the primary products arising from events in isolated molecules and not on those formed by secondary reactions, and there must be efficient detection and identification of the new species. Fortunately, most of the products become electrically charged as a result of the nuclear process, and, consequently, they can easily be deflected in electric and magnetic fields and detected by sensitive electronic devices. Radioactive species often produced in transformations can also be collected on charged electrodes, and the charge states of the species can be deduced from the manner in which the electric field affects the distribution of active material deposited on the various electrodes (*3*). In other experiments, the direct currents produced by the charged products are measured, and

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