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Climate Stabilization: For Better or for Worse?

Even if we could predict the future of our climate, climate control would be a hazardous venture.

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The world's climates have changed many times in the past, often with quite dramatic results, and they are changing today. We see the evidence in long-term trends in mean temperature, precipitation, variation of sea ice, and so forth. Furthermore, we experience seasonal anomalies in temperature and precipitation that affect large regions of the earth and influence agriculture and life patterns; these anomalies are also part of the set of statistics we refer to as climate. Understanding and predicting climate change has taken on considerable urgency now, since serious climate-induced food and water shortages have ravaged parts of Africa, threatened the livelihood of hundreds of millions of people in monsoon-dependent lands, and set off a spiral of increasing food prices.

So far, we do not have a comprehensive climate theory that can explain —much less predict—these trends and anomalies. Nevertheless, we understand enough about the earth-atmosphere system to recognize that humans can affect it, and surely have already, by pushing on certain "leverage points" that control the heat balance of the system. If we continue to expand our global activities, our influence on future climates will be still greater. As yet, however, we have given little serious thought to purposeful control of the climate.

If we could forecast climate changes we would be faced with several options. First, to do nothing. Second, to alter our patterns of land and sea use in order to lessen the impact of climate change. And third, to anticipate climate change and implement schemes to control it. The objective of climate control might be to reduce any natural changes, to counteract inadvertent human influence, or to cushion the effects of seasonal anomalies with a potentially disastrous social impact, such as the world experienced in 1972 and 1974 and may experience again in this decade. This is what we mean by stabilizing climate.

But if a climatic status quo is deemed a worthy objective, there are some serious problems to overcome before it can be realized. First is our present inability to predict what will happen if we do try to influence part of the climate system. Second is the difficulty of deciding what different peoples of the world will accept as an "optimum climate" toward which we should aim our stabilization schemes. Any imperfect climate modification (or conservation) scheme will have its winners and losers. How can we hope to satisfy the losers? After addressing these and other questions we consider some conceivable means of implementing climate control.

Causes of Climate Change

Given a fixed input such as solar radiation, the system that determines climate, on a regional or global scale, contains a variety of physical processes, many of which are fairly well understood individually. The biggest difficulties arise when we attempt to consider their interactions in nature, since these interactions create many feedback loops that act to amplify or dampen out small disturbances. In consequence, our climatic system is a highly nonlinear, interactive system that has defied a complete quantitative description. Figure 1 is a schematic representation of this system, presented here to illustrate its complexity.

So far we have no theoretical model that behaves like the climate system itself. Nevertheless, we do have models that incorporate many of the feedback loops and interactions that we now believe are most important (described below), and we are making progress in identifying the relative contributions of the dominant components of the system. This understanding, coupled with a large body of empirical and statistical evidence, gives some hope that soon we will be able to make more useful predictions of short-term climate change.

At the same time we must develop a quantitative theory of climate to understand better the factors that influence it in the longer term and to verify hypotheses and predictions derived from statistical methods. Human influence on climate, which may already be appreciable, can only be properly assessed when the natural forces at play are understood. Such a theory must include realistic modeling of atmospheric and oceanic subsystems, and these must in turn include the changing surface conditions of the planet and the masses of ice and snow at the poles.

Physical Factors Affecting the Climate; Feedback Mechanisms

The fundamental factors determining the overall climate of the earth-atmosphere system are the input of solar radiation, the earth's rotation rate, the

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mass and composition of the earth's atmosphere, the properties of the oceans, and the surface characteristics of land and sea. Over a sufficiently long time the unreflected portion of the incoming solar energy (that is, the part absorbed by the earth-atmosphere system) must be balanced by the planetary infrared radiation emitted to space. The temperature dependence of the latter therefore governs the mean temperature of the earth-atmosphere system and also the distribution of temperature within it.

While on a global average, and over a long period of time (more than a year), a near balance of planetary radiation is established, this is seldom true locally in time and space. Rates of solar heating and infrared cooling are highly variable, not only horizontally over the globe but throughout the vertical extent of the atmosphere. This unequal or differential heating of the globe, coupled with the rotation of the earth, is the ultimate driving force behind the motions we recognize as winds and ocean currents. These horizontal and vertical motions regulate the distribution of temperature, cloudiness, and precipitation over the globe.

The circulation systems become more vigorous with increasing north-south atmospheric temperature gradients, so that large-scale transient eddies (storm systems) which transport additional heat poleward provide "negative feedback," lessening the increase of the temperature difference from equator to pole (*1*). The atmosphere conveys heat in two forms: sensible and latent. Transport of sensible heat involves, for example, the direct transport of warm air to a cold region. Transport of latent heat involves the water vapor which is evaporated at the earth's surface and then transported by the atmosphere. Where the air is cooled below its dew point in the presence of suitable nuclei (particles) the water will condense into drops, thereby releasing the latent heat that was needed originally to change it from liquid water to water vapor. The process of evaporation, transport of water vapor, condensation, precipitation, and reevaporation (the hydrological cycle) is responsible for one-fourth to one-third of the net heat transported across the 30°N latitude circle, sensible heat transport by the atmosphere accounts for another one-fourth to one-third; and the oceans carry the remainder, between one-half and one-third of the total heat flowing poleword (*2–4*). Figure 2 shows the magnitudes of the various transport processes as a function of latitude.

No summary of important climatic factors would be complete (at least if long-term climatic changes are to be considered) without mention of the "cryosphere," which includes the substantial areas of the earth's surface that are covered by ice and snow. Snow and ice usually have much higher albedos (reflectivities) than uncovered land or open ocean. Thus, a "positive feedback" between ice cover and temperature is suspected: lower temperatures cause more ice and snow and thus higher albedos, which result in a reduction in absorbed solar energy, which in turn results in yet lower temperatures.

However, ice and snow are primarily confined to limited regions of the earth. Globally, clouds are the dominant reflectors of incoming solar energy (*5*). In general, the hydrological cycle (which includes the cycling of water in clouds and in snow and ice fields) looms as a major factor in determining mean surface temperatures, not only through its influence on snow, ice, and clouds, but also through its control of surface vegetation and soil moisture. Since the hydrological processes are also tied to the motions of the atmosphere and oceans, the radiation balance and the dynamics of the atmosphere-ocean-ice-land system are tightly coupled through the hydrological cycle as well as through the direct dependence of radiation on temperature, and any valid quantitative theory of climate will ultimately have to treat the hydrological cycle mechanisms in detail (*3, 6, 7*).

The chief purpose of this summary of physical factors that affect climate is to emphasize the coupled nature of the climate system (Fig. 1) and to intro-

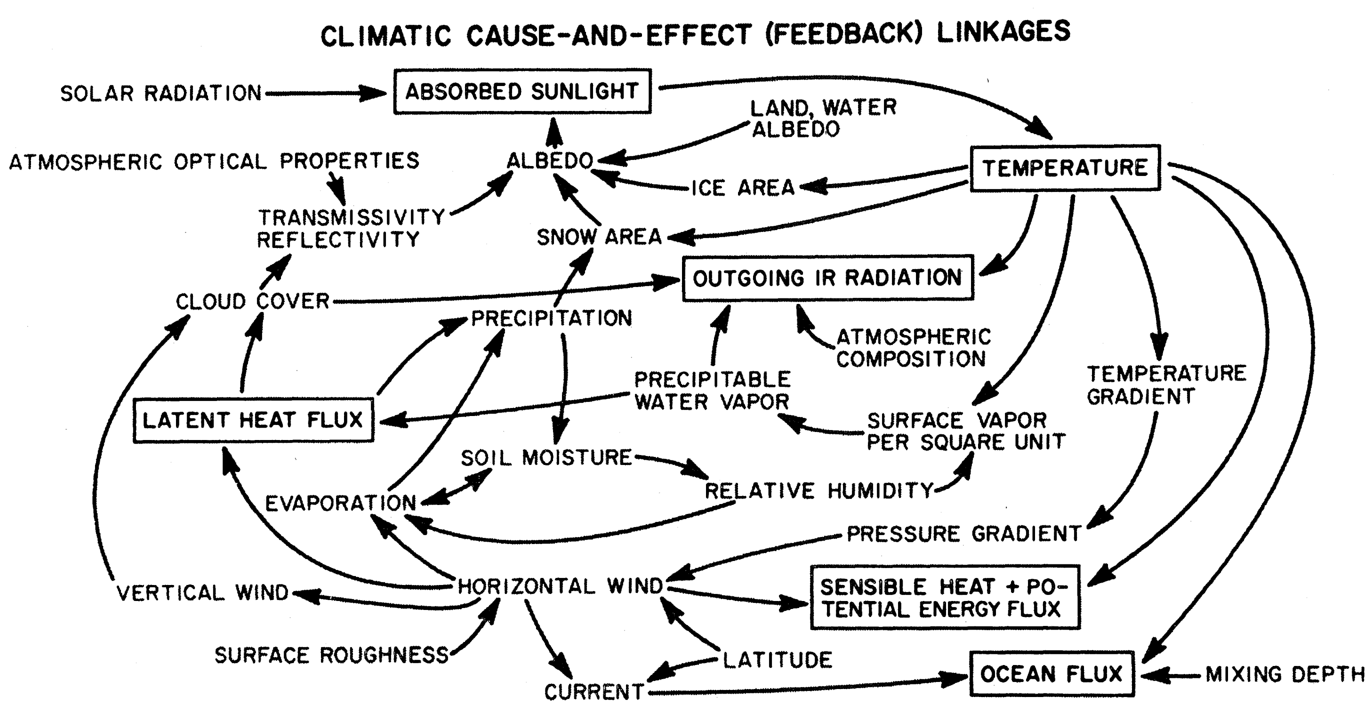

Fig. 1. The monumental challenge to atmospheric science to build a mathematical model that includes all important factors affecting the earth's climate is illustrated by this schematic figure of climatic feedback linkages. The chief difficulty is that many of these feedback processes have influences which are comparable in magnitude but opposite in direction (*43*); *IR*, infrared.

duce the important role of the numerous feedback mechanisms that operate in a physical system as complex as the earth-atmosphere system. The interactive, nonlinear nature of these climatic feedback mechanisms indicates that quantitative evaluation of how variations in any one of the system's factors affect the entire system will not be straightforward.

For example, if heat were added to the environment through human activities, we would expect the temperature of the atmosphere to rise. The amount of warming could be estimated relatively simply by comparing the magnitude of the heat input to the incoming solar energy through some straightforward radiative transfer and heat balance calculations. However, such an estimate presumes that all other factors remained constant—a highly tentative supposition. For example, the heat increment might evaporate more water and cause increased formation of clouds which would block out some sunlight and counteract the warming. Or, if the heat input were in a region with snow and ice cover, it might melt some of that frozen cover, leading to increased absorption of solar energy at the surface and a vastly accelerated warming. Or the cloudiness effect might cancel the ice and snow effect, or some other feedback process might dominate both of these, and so forth.

The range of possible interactions is staggering, but not necessarily fatal to the development of a comprehensive climate theory. We have a fairly good feel for the character of many of these feedback processes, and in numerous cases we can compute their effects with some confidence (*6–9*). Nevertheless, since individual interactions cause effects of opposite sign and comparable magnitude, the net consequence of the synergism of all climatic feedbacks is still uncertain.

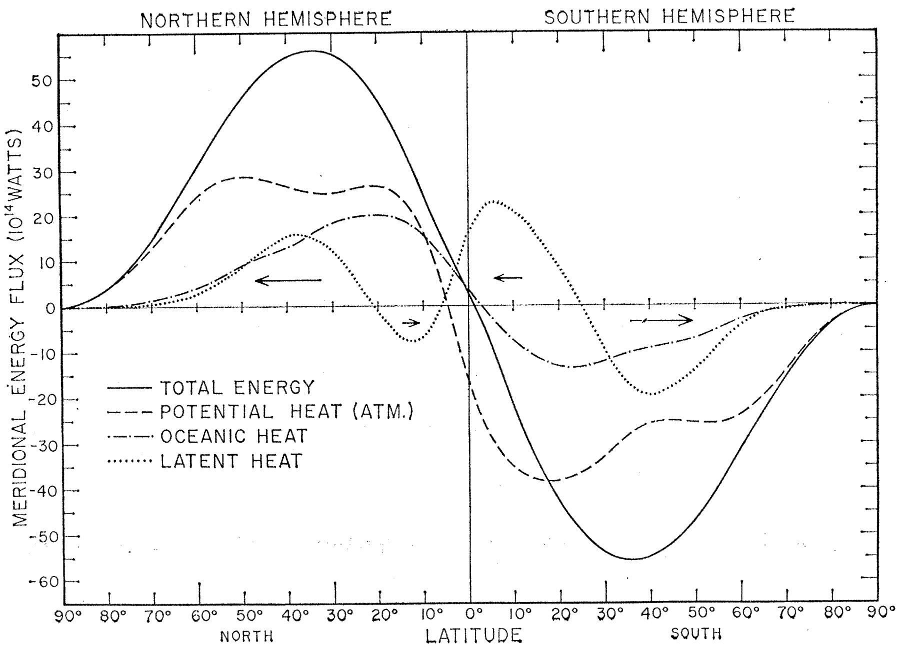

Fig. 2. Annual mean meridional flux of total energy for the earth-atmosphere system, and its apportionment between oceanic flux and atmospheric flux of potential heat and latent heat. The climate of each latitude zone is coupled to the climates of the other zones by the meridional fluxes of energy. [Source: Newton (*4*)]

Some Theories of Climate Change

There have been numerous theories of climate change, based on various combinations of the interacting physical factors. Changes external to the earth-atmosphere system are the most commonly postulated factors, and the theories treating them are the most deterministic. Such theories assume (reasonably) that the climate system responds to changed external forcing functions, for example: (i) fluctuations in solar emission, (ii) variations in the earth's orbit and axis of rotation, (iii) changes in the atmospheric carbon dioxide content, (iv) changes in the atmospheric dust content, and (v) changes in the character of the land surfaces.

While the first two factors are wholly external to the climate system (*10*), the last three could be coupled in certain ways to the climate (*6, 7, 11–13*). Natural changes in the carbon dioxide or dust content of the atmosphere or in land cover can depend on variables in the climatological state, such as wind (to carry dust), precipitation (to affect land cover), or temperature (to control the solubility of carbon dioxide in the oceans). Thus, these three factors are partially internal to the system. However, changes in these factors due to human activities (or to volcanoes) do not depend on the climatological state, and are thus external.

More recently, investigators have considered some factors that appear to be wholly internal causes of climatic change, such as (i) quasiperiodic or anomalous ocean surface temperature patterns (*14*), (ii) decreases in salinity in the North Atlantic or the Arctic Ocean, leading to increased sea ice formation (*6, 15*), and (iii) the almost-intransitivity of the climate system.

The last "cause" of climate change was proposed by Lorenz (*16*) to point out that an interactive system as complex as the oceans and atmosphere can have long-period self-fluctuations even with fixed external inputs. Internal fluctuations with time scales longer than the "standard" interval used to define a climatological average (sometimes taken to be 40 years) might easily be misinterpreted as climatic changes forced by external variations. Or, observed changes could be due to a combination (not necessarily linear) of external and internal forces.

This discussion suggests the inherent difficulty of tracing cause and effect for any climate change when climate is defined as a time average over a finite interval. Furthermore, climatic fluctuations which people would consider significant (such as seasonal anomalies) could occur on time scales shorter than any particular climate-defining interval, and might be interpreted as climatic "noise" due to short-term averaging of random, unpredictable weather events. Yet these anomalies should still be considered part of the climatic state, since it may be shown that the frequency of their occurrence is related to longer-term climatic statistics.

Therefore, merely to identify the existence of a climate change requires the skill to separate changes in the longer-term mean (the signal) from shorter-term weather fluctuations (the noise) (*8, 17*). Then to attribute cause and effect necessitates separation of internal and external forcing factors quantitatively, a step that requires a theory of climate. While at present no completely satisfactory theory exists, many of its elements are understood, and the major tools for such understanding are climate models.

Climate Modeling

The factors affecting climate must all obey the principles of conservation of mass, momentum, and energy. These laws, together with thermodynamic and chemical laws governing changes in the material composition of land, ice, sea, and air, comprise the basis for a theory of climate. Mathematically expressed, these form a coupled set of three-dimensional time-dependent nonlinear partial differential equations, whose solutions can be obtained in principle if the initial state of the system and its external forcing boundary conditions are known (*6*).

Unfortunately, in order to solve the equations of climate theory with the knowledge and tools available to us in the foreseeable future it is necessary to ignore the details of small-scale processes, treating the system at a discrete number of points (or modes) in space (the grid) and in time (the time step). All processes occurring on scales smaller than those resolved in the model must be ignored or, at best, treated in a statistical fashion. The method of relating statistically the effects of subgrid-scale processes to those occurring on a much larger scale is called parameterization. The technique of selecting the appropriate grid size, time step, parameterization schemes, and even approximations to the basic equations is the art of modeling, and the particular choice of these elements defines the climate model (*6, 8, 18*).

The simplest types of climate models recognize the fundamental importance of the radiation balance in determining temperature, and bypass the problems inherent in dealing with a horizontal grid. These merely relate the vertical fluxes of infrared and solar radiation in the atmosphere to the atmospheric temperature profile and the vertical distribution of optically important gases, clouds, and particles. An assumption that ties the atmospheric lapse rate, or decrease of temperature with height, to vertical convective motion is usual for this class of model.

These "horizontally averaged models" are often most useful in globally averaged form, and can tell us the relative importance of different optically important constituents for the radiation balance and temperature distribution of the earth-atmosphere system. For example, the effect of increased atmospheric carbon dioxide has been studied by Manabe and Wetherald (*19*) with a radiative-convective model of the earth-atmosphere system. Despite the fact that all feedback processes associated with the horizontal redistribution of energy were absent in their model, it is widely cited as giving an order of magnitude estimate of the increase in surface temperature resulting from increased carbon dioxide.

A second kind of modeling approach is to work only with the energy balance of the earth-atmosphere system at each latitude and to parameterize by semiempirical relations the horizontal transports of heat in terms of mean latitudinal temperature difference. This has been the approach of Budyko (*20, 21*) and Sellers (*22*), who included the surface temperature–ice–albedo feedback effect. Their well-known semiempirical approach gave their models a greater sensitivity to small changes in the radiation balance than that of horizontally averaged models, which do not include the positive feedback effect of surface temperature–ice–albedo coupling. The work of Budyko and Sellers has led to concern over the stability of the earth's climate, since negative changes in energy input of the order of 1 percent of the solar constant could plunge their model climates into an ice age or, alternatively, positive changes could significantly melt the polar ice caps. Further insight into the behavior and limitations of these models has been given by Schneider and Gal-Chen (*23*), among others.

These examples show the importance of zonally averaged energy balance models in estimating to first order the effect of a change in a climatic component, but they also remind us that any feedback processes not properly included could substantially revise these estimates.

Models that include many coupled processes have been developed, but as the number of processes included and the spatial and temporal resolution are increased, so is the computation time—drastically. Three-dimensional simulations of the general circulation of both atmospheric and oceanic systems have been made, and in many instances large-scale features predicted by these models are beyond our intuition or our capability to measure in the real atmosphere and oceans. Nevertheless, while general circulation models (GCM's) are essential tools for evaluating the relative magnitudes of competing feedback processes, they may not be practical tools for long-term climate forecasting for many years (except possibly for seasonal or interannual forecasts).

Finally, it may be possible to develop a compromise model, which will probably be three dimensional, but with a sufficiently limited resolution (or coarse grid) that very-long-term integrations may be possible. Such a "statistical-dynamical" approach will require parameterization of processes that are underresolved by the coarse grid. These parameterizations could be based on a limited number of experiments with high-resolution general circulation models. Then, once the statistical-dynamical models had been calibrated against GCM's, it would remain to calibrate them and the GCM's against the real climate.

A few cautious steps along these lines are being taken at a handful of institutions around the world. The success of such efforts will determine to a large extent our potential for understanding climatic cause and effect, and will indicate the degree to which long-term climate prediction is possible.

Society's Leverage Points

The degree to which people can change the climate generally depends on the scale of the attempt. Wearing warm clothes on a cold day is probably the smallest scale, heating and cooling the air in a house is a slightly larger conventional undertaking, and changing the air temperatures (and air quality) over a large city is now quite commonplace also—although not planned. Other climate changes on a larger scale have certainly occurred because of human activities, although they are harder to document [for example, desert growth along the erstwhile "Fertile Crescent" of the Mediterranean has been attributed by some to overgrazing of goats (*6*)].

The key to any climate change is an alteration of the heat (or water) balance of the system involved. Thus, in winter the city adds primarily heat directly to the atmosphere, thereby warming it; and in summer, in addition to heat directly added, the greater heat conductivity of the materials of buildings and pavements causes the city to retain its heat at night longer than the surrounding countryside. Changing the reflectivity of the surface (such as by irrigating a desert or cutting down a forest) changes the absorption of sunlight and also influences the evaporation of water from the surface. Damming rivers (changing the hydrologic cycle), clearing land by the slash-and-burn approach (creating clouds of smoke), and doing many other things to alter the face of the land and its heat balance all contribute to climate change on a regional scale (*6*).

On a global scale human influence can now begin to be felt. While our climate models are still incomplete, we do understand enough about the system to be able to estimate the initial effect of changing some specific factor. One such factor is the ability of the atmosphere to absorb infrared radiation emitted by the ground; a change in the atmospheric content of carbon dioxide, water vapor, or ozone will have such an effect, since these are all optically important gases (*7*).

The increased use of fossil fuels since the beginning of the industrial revolution has resulted in a steady buildup of the carbon dioxide content of the atmosphere. This gas is chemically quite stable, and somewhat less than half of the added carbon dioxide appears to have gone into the oceans and the biosphere (mostly the forests), while the other half has remained in the atmosphere. It is estimated (*6*, p. 237; *11*, *24*) that the atmospheric content of carbon dioxide has risen from a pre-industrial revolution value of slightly under 290 parts per million (ppm) by volume to about 320 ppm, and that by the end of the century it may rise to 380 ppm (*24*) or about 400 ppm (*11*). (The energy crisis may have an influence on both of these estimates, but it seems probable that coal will continue to be used in increasing amounts to replace gas and oil—unless advocates of reduced economic growth have a persuasive impact on present trends.)

Estimates of the effect on climate of the increase in carbon dioxide expected by A.D. 2000 depend somewhat on the assumptions that are made about the other adjustments that the climate system will make to compensate for the increased absorption of infrared radiation. (For example, how much more water vapor will be taken up by a warmer lower atmosphere?) However, 0.5°C seems to be a reasonable first-order estimate for the average rise in the temperature of the lower atmosphere due to a 20 to 25 percent increase in atmospheric carbon dioxide. We believe there will be relatively less change at low latitudes and perhaps twice the average change (or more) in polar regions, as calculated by Manabe [discussed in (*18*)]. For perspective, it is helpful to note that 0.5°C is approximately the magnitude of surface temperature warming experienced by the Northern Hemisphere between about 1900 and 1945. This seemingly small increase can still produce dramatic changes in some places (compare Fig. 3 with the cover photograph). Thus, anthropogenic carbon dioxide increases projected to the year 2000 could be as

Fig. 3. Photograph of the town of Argentierre in the French Alps, taken in the mid-1960's. The view is essentially the same as that in the engraving shown on the cover of this issue, which was made about 100 years earlier when the mean hemispheric temperature was less than 0.5°C cooler. The terminus of the glacier can now barely be discerned in the upper part of the picture. [From Laurie (*44*)]

influential in changing the climate as the processes active in the climatic system in the first half of this century.

If this increase continues until the atmospheric carbon dioxide doubles by about A.D. 2040 (*11*), it is doubtful that the present boundaries of glaciation or sea level will be maintained.

At the same time that humans have been adding carbon dioxide to the atmosphere, they have been adding particles, or aerosols. These aerosols come from direct injection by coal-burning plants and furnaces or by slash-and-burn practices, or they are created photochemically in the atmosphere from unburned hydrocarbon fuel and sulfur dioxide under the influence of solar ultraviolet radiation. Measurements at many places have shown a steady rise in the aerosol content of the lower atmosphere in the past few decades, and sudden increases in the stratospheric aerosol content have followed the major volcanic eruptions such as the eruption of Mount Agung in Bali in 1963.

The long-term aerosol record for the globe is far from clear, however. A particle floating in the lower atmosphere at middle latitudes will have a mean lifetime of only 3 to 4 days, since the atmosphere cleanses itself by rain (*25*). In polar regions the lifetime of particles is probably longer, and in the rainy parts of the tropics even shorter. Thus, the reported increases in aerosol content are most noticeable near the sources (except for volcanic aerosols, which remain in the stratosphere for several years and are spread worldwide), and vast regions of the world, including most of the Southern Hemisphere, have apparently experienced virtually no increase in anthropogenic aerosols. The increase is most pronounced downwind from the industrialized parts of the Northern Hemisphere and in tropical regions where slash-and-burn practices are widespread (*26*).

In regions where aerosols have increased, an effect on the heat budget will be felt, since aerosols efficiently scatter and absorb solar radiation. Over land with a moderately high surface reflectivity, typical tropospheric aerosols will tend to warm the atmospheric column in which they lie and decrease the solar flux reaching the surface. Over the oceans, which have low reflectivity, the net effect will be a cooling, since relatively more sunlight will be reflected back to space when aerosols are introduced over the dark surface. Several studies have been made of the overall effect of aerosols on the radiation or heat balance of the earth-atmosphere system, and given the (meager) available data the consensus appears to be slightly in favor of a cooling (*7, 13*). In fact, addition of aerosols has been invoked by some to explain the cooling trend in the Northern Hemisphere that set in about 1945. [For two somewhat different assessments of this point the reader is referred to Bryson (*27*) and Mitchell (*12, 28*).]

Aerosols not only affect the radiation balance, but certain kinds of particles can serve as ice nuclei (below 0°C) and condensation nuclei (in warm clouds) and thereby influence the formation of clouds and precipitation. It has been pointed out (*29*) that this could be an even greater leverage point than the radiation effect, but so far we cannot assess the direction of this effect, let alone its overall magnitude.

So far we have dealt with some leverage points that mankind could use to control the radiational heat balance of the climate system, and thereby influence the climate. In the foreseeable future anthropogenic sources of energy may become a factor in the global heat balance by their sheer magnitude. Just as the air over our large cities is now warmed by the heat released locally, society's activities in the future will warm the air perceptibly over large regions, and quite possibly over the entire earth (*30*).

Consider the present man-made energy released to the atmosphere compared to the solar energy that is absorbed at the surface. The power generated artificially worldwide amounted to (6 to 8) $\times 10^3$ gigawatts in 1970 and was increasing at a rate of 5.7 percent per year (*6*). (This was the estimated power output of all generators, factories, automobiles, heating plants, and so forth, all ending up in the environment in the form of heat. It was considerably larger than the useful power that turned our wheels.) The solar power that is absorbed at the surface is, on the average, about 150 watts per square meter, and for the whole earth this amounts to 7.5×10^7 gigawatts. Thus, on a global scale mankind generates only about 0.01 percent as much energy as the sun deposits at the surface.

Now consider a future "postindustrial society" as seen by the technological optimists, such as Weinberg and Hammond (*31*). A century from now, in about A.D. 2100, the present energy crisis will have long since been solved; nuclear, thermonuclear, solar, coal, and perhaps other forms of power generation will provide adequately for a population of, say, 20 billion people; and the reduction of pollution and extraction of resources from the earth will require high technology and will be more expensive in terms of energy than they are now. A scenario of the future can be drawn up that shows such a world to be technically possible, the main assumption being that society itself will survive. [The author of this scenario must, of course, be both a technological and a social optimist, and there are many who do not share this optimism, such as the Club of Rome or Heilbroner (*32*).]

Twenty billion people, each of whom uses four times the present U.S. per capita power consumption of 10 kilowatts, would require 8×10^5 gigawatts, and this is about 1 percent of the total solar power absorbed at the surface. (Note that the power generated would be localized on the continents, which comprise only one-fourth of the earth's surface area.) The horizontally averaged climate models show that a 1 percent increase in thermal power would raise the average temperature of the climate system by about 1°C, and zonally averaged energy balance models (including ice-albedo feedback) raise this estimate by a factor ranging from 1.3 to 3.0. Such a change would be less at equatorial latitudes and several times larger at the poles if the heating were more or less evenly distributed over the continents. These large polar changes are especially noteworthy, since they have important implications for the Arctic Ocean, the Greenland ice cap, the Antarctic ice cap, and the sea level, but this is beyond the scope of this article (*6, 9, 30*).

The lesson to be learned from this exercise is that the future physical influence of mankind can be very significant relative to that of nature. Furthermore, with so much power under its control mankind will very likely have the technological capability to alter climate purposefully as well as inadvertently. Leaving aside for the moment the question of whether it makes sense to alter or conserve climate, we will review some of the schemes that have been suggested for modifying climate on a hemispheric or global scale—

schemes that have so far been considered to be on the fringe of science fiction. The range of possibilities widens rapidly if one imagines the financial resources of the major world powers available to carry them out. These schemes are summarized in Fig. 4, and some of them will be described briefly.

One perennial suggestion—none of these should be considered yet as proposals—is to eliminate the Arctic Ocean ice pack. This layer of drifting ice that covers most of the Arctic Ocean varies in average thickness from less than 2 meters in summer to about 3 meters in the late winter (*33*), and if it were removed the characteristics of the northern polar regions would be dramatically different. An open ocean would result in much more moderate and quite possibly more snowy winters around the Arctic Basin, with January temperatures some 10° to 15°C warmer than at present (*33, 34*). We do not know whether this could start another glaciation of northern Canada and Europe due to the increased snowfall, but this is a definite possibility. Furthermore, a change as large as eliminating the Arctic sea ice would almost surely cause important climatic changes in places far from the Arctic Basin. The question now is how to eliminate the ice pack. Of course, the temperature rise in the Arctic due to carbon dioxide or global thermal pollution that we have just described might be sufficient without any extra effort (*21*), but there are some ways to help the process along.

Spreading black particles, such as soot, by cargo aircraft is one way. A 20 percent decrease in reflectivity of a large area of the ice would cause it to disappear in a period of about 3 years, according to one model (*35*). Another suggestion is to dam the Bering Strait and pump water from the Arctic Ocean into the Pacific, thereby drawing warm Atlantic water in from the other side and raising the surface water temperature enough to melt the ice pack. A third way might be to detonate "clean" thermonuclear devices in the Arctic Ocean to fragment the ice and stir saltier, warmer water from below. Diverting northward-flowing rivers that add fresh water to the Arctic Ocean would speed the process, since the present surface layer of low salinity (and lower density) a few tens of meters deep is partially replenished by these rivers, and if it were eliminated the pack ice would grow less rapidly in winter (*6*). Other ideas will no doubt come to mind, but these may suffice to give the flavor of the argument.

It has also been suggested that a massive extension of present cloud-seeding techniques could modify precipitation patterns and the release of latent heat on a regional or hemispheric scale. The regular "steering" of hurricanes (or typhoons, as they are called in the western Pacific) by cloud seeding, if that turns out to be feasible, would change the climate of hurricane-prone regions. An alternative way of steering hurricanes might be to pump cold water to the surface before them, since hurricanes are known to respond to the surface temperature of the ocean. (Incidentally, a proposal to systematically direct hurricanes headed for the southern United States would

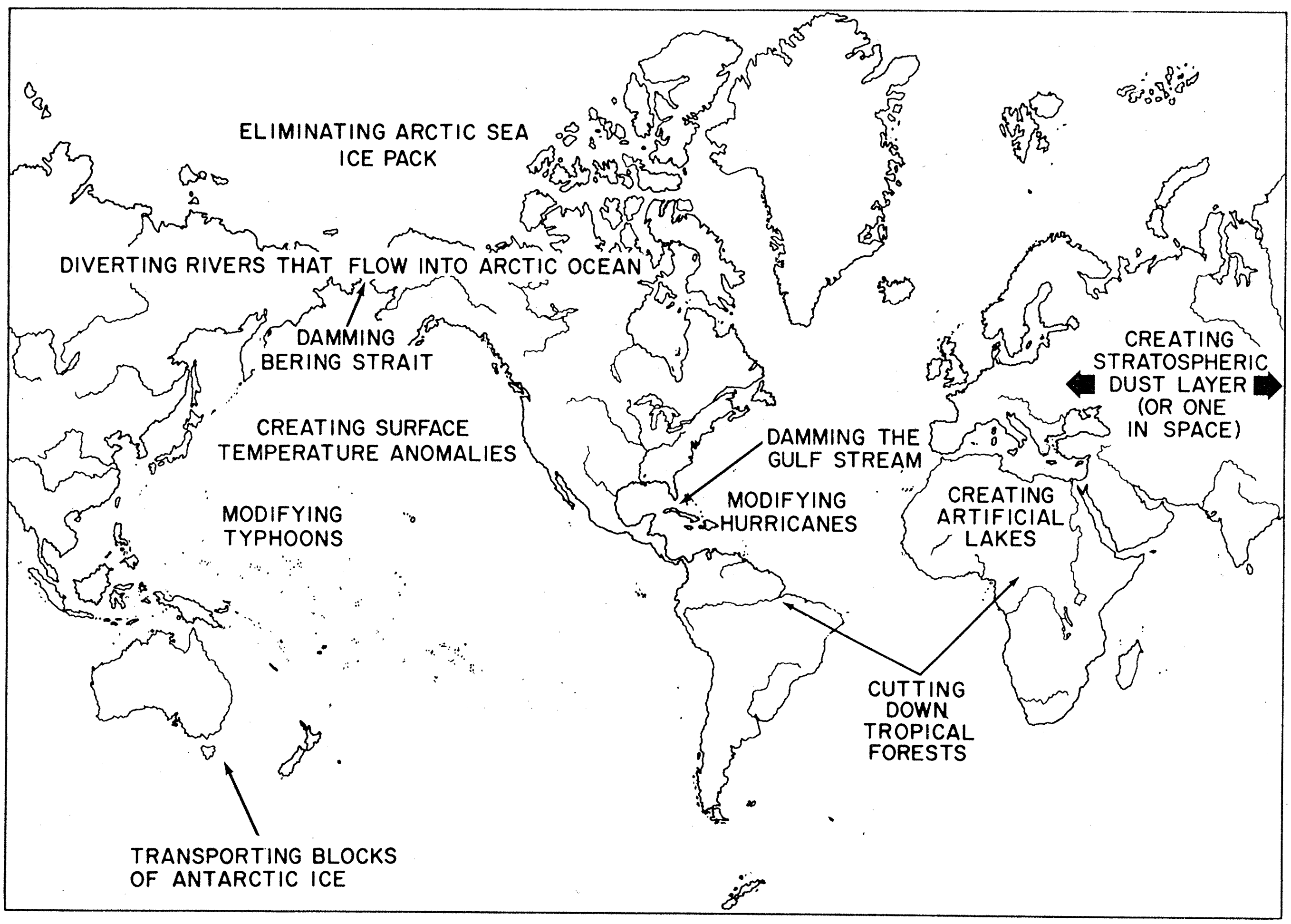

Fig. 4. Schematic illustration of the kinds of engineering schemes that could be proposed to modify or control the climate.

raise some concern south of the border, since the Gulf Coast of Mexico enjoys the rainfall from these same hurricanes. This is an example of the kind of conflict of interest that we will discuss further in the next section.)

As we mentioned above, certain aerosol particles have a tendency to cool the earth on the average, and when they are injected into the stratosphere they remain there for several years and have a more prolonged cooling effect at the surface. Thus, if we were concerned about a general rise in temperature due to carbon dioxide and thermal pollution, why not inject enough of the right kind of particles into the stratosphere to counteract the warming? Perhaps a fleet of supersonic transports would help here, since they could create a kind of "stratospheric smog" at about the right level (*6, 36*). In an even more fanciful vein, why not put bigger particles (or mirrors) in orbit around the earth, where they may remain even longer?

One could go on with such suggestions, some to cool and some to warm vast regions of the earth, some to change the patterns of rainfall, some to protect from damaging storms, and so forth. They could be used to improve the current climate (for some) or to offset a predicted deterioration of climate (for some), whether the deterioration was natural or man-induced. In the next section we will discuss the pertinent question of whether we should use any newly acquired powers for climate control or climate stabilization.

Hazards of Climate Modification

Returning to our original thesis, we believe that it would be dangerous to pursue any large-scale operational climate control schemes until we can predict their long-term effects on the weather patterns and the climate with some acceptable assurance. We cannot do so now, and it will be some time—if ever—before we can. To tamper with the system that determines the livelihood and life-styles of people the world over would be the height of irresponsibility if we could not adequately foresee the outcome. However, we recognize that this may not be the opinion of some, especially those who live in the affected regions where a prediction of climatic change could be a forecast of local disaster if the predicted change were not offset.

In addition, there is need to prevent one group from using a climatic "threat" (real or imagined) by a neighboring group as a pretext for hostile actions (*37*). For example, by analogy, it is not without precedent for one Middle Eastern state to claim water rights to a river that is also vital to its neighbor, and for the neighbor to demonstrate, in the clearest terms, the consequences to the first of any diversion of the disputed river. In that case vital interests and raw power determined the course of action for those states, not rational discourse or the principles of right and wrong. In another case the United States has negotiated with Mexico over rights to the water from the Colorado River.

In the case of water rights, legally tangled though it is, it is still easy for one state to determine whether the other has effected a physical change and to assess the magnitude of that change. However, in the case of weather or climate modification (inadvertent or purposeful), it would probably be much more difficult to establish the agent and degree of responsibility for any detectable effects.

As a case in point, consider the Rapid City, South Dakota, flood of 9 June 1972. Experts have argued about whether prior cloud-seeding experiments contributed to the damage (*38*). We suspect that all but the most partisan antagonists still have reasonable doubts about the magnitude of the contribution, if any, of the seeding program. The fact remains that it is nearly impossible at present to establish conclusively cause and effect linkages (let alone magnitudes) in any single weather or climate modification experiment. In the Rapid City case there is an accepted legal authority to adjudicate potential disputes, and the ultimate ruling of the courts can be enforced. But suppose one of the bitter enemies in the Middle East were conducting weather modification experiments and its neighbor downwind felt aggrieved. Would the matter more likely end in the World Court—or in some form of military action?

Since cause and effect are hard to unravel and since no formally assembled body of impartial experts is in existence, blame would be difficult to assess. What is worse, perhaps, is that experts around the world would probably align themselves with the combatants on politically, rather than scientifically, defensible grounds if a climate-related dispute flared. Since progress in climate research necessarily depends on cooperative working relations between scientists of rival powers, the potential damage to scientific progress from a scenario like this is frightening.

Perhaps we should consider the creation of a panel of "impartial" international experts to adjudicate (or at least mediate) such disputes before one explodes. It may be too late if a conflict were to occur first, with polarization and partisanship being an accepted factor in world diplomacy. How would power be assigned to such a panel? How would its constituency be determined? These questions are as familiar and nearly unanswerable as those that accompany any effort to share power and responsibility multinationally.

Yet, we cannot escape the fact that the atmosphere is a resource that is shared by all the world's people, and is a tightly coupled system that cannot be pushed very hard in one place without making a bulge somewhere else.

Coming back to our central theme, suppose a climate disaster were forecast: wouldn't some countries propose climate stabilization measures? And, granted that they could agree among themselves to try to stabilize the climate, who would implement the stabilization scheme? In view of the potential for economic or military advantage, who would deal with errors or side effects that might affect a third party—that is, if a cause and effect chain could be established beyond a reasonable doubt?

We have raised many more questions than we are even remotely capable of answering, but we do wish to offer one "modest" proposal, for "no-fault climate disaster insurance." If a large segment of the world thinks the benefits of a proposed climate modification scheme outweigh the risks, they should be willing to compensate those (possibly even a few of themselves) who lose their favored climate (as defined by past statistics), without much debate as to whether the losers were negatively affected by the scheme or by the natural course of the climate. After all, experts could argue both sides of cause and effect questions and would probably leave reasonable doubts in the public's mind.

Short-term deterioration of climate strikes hardest at food production, whereas longer-term changes might be accommodated by changing the pattern of agriculture and perhaps by migration. This suggests that the form of reimbursement for climate-induced losses should, at least initially, be in the form of food or food-production technology. It follows that the international insurance agency that issues the no-fault climate disaster insurance must be a holder of adequate reserves of food to reimburse the losers, together with the means to transport it where it is most needed.

A special form of such an insurance program makes sense already, in the absence of any intent to modify climate purposefully. Crop failures and famine have recently struck marginal areas of Africa south of the Sahara Desert (the Sahel) and monsoon-dependent India and Pakistan, and these failures must be attributed in part to climate variation. The cold winter and hot dry summer of 1972 in the central Soviet Union caused subnormal wheat yields, which led to a shift of international trade balances as the Soviet Union bought U.S. wheat in unprecedented quantities (*39*). All this strongly suggests that, in view of the present dwindling world reserves of food (enough grain for about 1 month, or perhaps less), there should be an urgent international effort to cushion the shock of future crop failures by creating stockpiles of food. This could be called, for the time being, "No-fault famine insurance"—or, as Schneider (*40*) recently suggested, referring to the story of Joseph in Egypt, "the Genesis strategy." Perhaps a push to increase global food supplies might also generate pressures for climate modification or control operations (*41*). However, it seems to us that control of food supply and demand is a far better method of reducing famine than attempts to control the climate.

A less ambitious trial of our original insurance plan to cover situations where weather modification efforts are taking place could be made within one country. This may be appropriate even now. Returning to the Rapid City case, for example, if the people of South Dakota had agreed in the majority that weather modification operations were likely to do more good than harm for the greatest number of people in the state, then a statewide insurance premium could have been levied and a no-fault weather modification insurance policy could have been issued to every citizen who could be affected by the operation. Of course, it could be argued that natural variability in the atmosphere (such as the risk of a damaging storm occurring in spite of the weather modifying operation) may be great enough to raise the premiums for our weather insurance beyond a level that the majority would find acceptable. This might curtail potentially valuable projects. But, until cause and effect can be traced with more certainty, it seems to us that compensation as well as benefit must be spread more equitably among all potentially affected people.

In this proposition we are referring to operational weather or climate modification projects, not to small-scale research experiments. The latter are crucial to the acquisition of the kinds of understanding that will ultimately lead to knowledge of cause and effect. Even in these limited projects, however, cooperation of those affected locally is essential to the experiment's success (*42*).

Even granted the ability to predict the effects of a perturbation to the system, or the ability to forecast seasonal anomalies some months in advance—and we are hopeful that this can be done in the decades ahead—and granted the existence of some semiperfect operational scheme to stabilize the climate, there will still be the agonizing decision about whose climate should be preserved, whose improved, and whose sacrificed. (Take, for example, the differing attitudes of the United States and Mexico toward hurricanes in the Gulf of Mexico, cited in the previous section.) Perhaps agreement could be reached (unless one lived in drought-prone central Africa) if it were simply a matter of stabilizing the present climate or preserving the status quo. But we have no international mechanism or institution or treaty for deciding what would be an overall improvement, let alone tackling the question of who would be responsible if a scheme produced (or were perceived to produce) unexpected results in someone else's backyard.

It may be useful now to summarize some important points and questions we have discussed in connection with potential climate-related conflict situations.

1) The atmosphere is a highly complex and interactive resource common to all nations.

2) Decision-making with unsharpened tools (such as climate models) may become necessary.

3) What if we could trace climatic cause and effect linkages? Accusations would abound.

4) What if one nation perceived climatic cause and effect linkages? Could this be used as an excuse for hostility?

5) What if one nation could predict climate? This would change entire international economic market strategies or might lead to pressures for climate control.

6) Who would decide and who would implement climate modification and control schemes? The costs of miscalculation (or perception of miscalculation) are immense.

We have the impression that more schemes will be proposed for climate control than for control of the climate controllers. Whether or not purposeful climate control is ever needed or realized, the problems of inadvertent climate modification, climate prediction, and feeding a growing world population suggest the timeliness of studying potential climate-related crisis and conflict scenarios. This is the first step. In any case, the object of understanding and anticipating natural, inadvertent, or purposeful climate change and its consequences for society must, in our view, continue to be a major interdisciplinary goal. While it is essential to work out international mechanisms to guarantee that any new knowledge of our climate system will have only constructive uses, the price in human suffering of continued ignorance of the causes of climate change may already have become unacceptably high.

References and Notes

1. P. D. Thompson, *Numerical Weather Analysis and Prediction* (Macmillan, New York, 1961), p. 118; E. N. Lorenz, *The Nature and Theory of the General Circulation of the Atmosphere* (Report No. 218, World Meteorological Organization, Geneva, Switzerland, 1967); H. H. Lamb, *Climate: Present, Past and Future* (Methuen, London, 1972), vol. 1; P. H. Stone, *J. Atmos. Sci.* **30**, 521 (1973).
2. W. D. Sellers, *Physical Climatology* (Univ. of Chicago Press, Chicago, 196. T. H. Vonder Haar and V. E. Suomi, *J. Atmos. Sci.* **28**, 305 (1971); T. H. Vonder Haar and A. H. Oort, *J. Phys. Oceanogr.* **3**, 169 (1973).
3. M. I. Budyko, *Climate and Life* (Hydrological Publishing House, Leningrad, 1971).
4. C. W. Newton, *Meteorol. Monogr.* **13** (No. 35), 242 (1972).

S. H. Schneider, *J. Atmos. Sci.* **29**, 1413 (1972).

6. SMIC report, *Inadvertent Climate Modifications; Report of the Study of Man's Impact on Climate* (MIT Press, Cambridge, Mass., 1971).
7. S. H. Schneider and W. W. Kellogg, in *Chemistry of the Lower Atmosphere*, S. I. Rasool, Ed. (Plenum, New York, 1973), p. 203.
8. S. H. Schneider and R. E. Dickinson, *Rev. Geophys. Space Phys.* **12**, 447 (1974).
9. W. W. Kellogg, in *Proceedings of the 24th Alaskan Science Conference* (Univ. of Alaska Press, Fairbanks, in press).
10. ———, *Acta Astron.* **1**, 81 (1974); J. M. Mitchell, Jr., *Quat. Res.* **2**, 436 (1972).
11. R. Bacastow and C. D. Kelling, in *Carbon and the Biosphere*, G. M. Woodwell and E. V. Pecan, Eds. (USAEC CONF-720510, National Technical Information Service, Springfield, Va., 1973), p. 86.
12. J. M. Mitchell, Jr., in *Global Effects of Environmental Pollution*, S. F. Singer, Ed. (Reidel, Dordrecht, and Springer-Verlag, New York, rev. ed., in press).

13. S. I. Rasool and S. H. Schneider, *Science* **173**, 138 (19 → G. Yamamoto and M. Tanaka, *J. Atmos. Sci.* **29**, 1405 (1972).
14. J. Namias, in *The Changing Chemistry of the Oceans*, D. Dyrssen and D. Jagner, Eds. (Wiley, New York, 1972), p. 27.
15. S. Martin and P. Kauffman, *J. Fluid Mech.* **64**, 507 (1974); P. K. Weyl, *Meteorol. Monogr.* **8** (No. 30), 37 (1968).
16. E. N. Lorenz, *J. Appl. Meteorol.* **9**, 325 (1970); in *Man's Impact on the Climate*, W. H. Mathews, W. W. Kellogg, G. D. Robinson, Eds. (MIT Press, Cambridge, Mass., 1970), p. 179; *Meteorol. Monogr.* **8** (No. 30), 1 (1968).
17. C. E. Leith, *J. Appl. Meteorol.* **12**, 1066 (1973); R. M. Chervin, W. L. Gates, S. H. Schneider, *J Atmos. Sci.*, in press.
18. J. Smagorinsky, in *Weather and Climate Modification*, W. N. Hess, Ed. (Wiley, New York, 1974), p. 633.
→ S. Manabe and R. T. Wetherald, *J. Atmos. Sci.* **24**, 241 (1967).
20. M. I. Budyko, *Tellus* **21**, 611 (1969).
21. ———, *Eos Trans. Am. Geophys. Union* **53**, 868 (1972).
→ W. D. Sellers, *J. Appl. Meteorol.* **8**, 392 (1969); *ibid.* **12**, 241 (1973).
23. S. H. Schneider and T. Gal-Chen, *J. Geophys. Res.* **78**, 6182 (1973).
24. L. Machta, in *Carbon and the Biosphere*, G. M. Woodwell and E. V. Pecan, Eds. (USAEC CONF-720510, National Technical Information Service, Springfield, Va., 1973), p. 21.
25. E. A. Martell, in *Man's Impact on the Climate*, W. H. Mathews, W. W. Kellogg, G. D. Robinson, Eds. (MIT Press, Cambridge, Mass., 1971), p. 421.
26. W E. Cobb, *J. Atmos. Sci.* **30**, 101 (1973); L. Machta and K. Telegadas, in *Weather and Climate Modification*, W. N. Hess, Ed. (Wiley, New York, 1974), p. 687.
27. R. A. Bryson, *Weatherwise* **21**, 56 (1968); *Climatic Modification by Air Pollution, II: The Sahelian Effect* (Institute for Environmental Studies, University of Wisconsin, Madison, 1973); *Science* **184**, 753 (1974).
28. J. M. Mitchell, Jr., in *Man's Impact on the Climate*, W. H. Mathews, W. W. Kellogg, G. D. Robinson, Eds. (MIT Press, Cambridge, Mass., 1971), pp. 133 and 167.
29. P. V. Hobbs, H. Harrison, E. Robinson, *Science* **183**, 909 (1974).
30. W. W. Kellogg, in *The Energy Question*, E. W. Erickson and L. Waverman, Eds. (Univ. of Toronto Press, Toronto, 1974), p. 242.
31. A. M. Weinberg and R. D. Hammond, *Am. Sci.* **58**, 412 (1970).
32. Club of Rome, *Ecologist* **2**, 1 (1972); R. L. Heilbroner, *An Inquiry into the Human Prospect* (Norton, New York, 1974).
33. J. O. Fletcher, *The Heat Budget of the Arctic Basin and Its Relation to Climate* (Report R-444-PR, Rand Corporation, Santa Monica, Calif., 1965).
34. M. Warshaw and R. R. Rapp, *J. Appl. Meteorol.* **12**, 43 (1973).
35. G. A. Maykut and N. Untersteiner, *J. Geophys. Res.* **76**, 1550 (1971).
36. SCEP report, *Man's Impact on the Global Environment: Study of Critical Environment Problems* (MIT Press, Cambridge, Mass., 1970); C. E. Leith, Ed., *The Natural and Radiatively Perturbed Troposphere* (CIAP Monograph 4, Department of Transportation, Washington, D.C., in press).
37. S. H. Schneider, paper presented at the Annual Meeting of the AAAS, December 1972, Washington, D.C.; *New Eng.* **7**, 14 (1973).
38. B. C. Farhar, *Bull. Am. Meteorol. Soc.* **55**, 759 (1974).
39. L. A. Mayer, *Fortune* **84** (No. 2), 85 (1974).
40. S. H. Schneider, *National Observer*, 6 July (1974), p. 18; see also R. F. Taubenfeld and H. J. Taubenfeld, *International Organization* **23**, 808 (1969).
41. ———, *Ambio* **3**, 150 (1974). In the same issue of *Ambio* (p. 120) M. Falkenmark and G. Lindh suggest: "It would, for instance, be of interest to suppress part of the copious rains in Cameroon, Nigeria, and other coastal states to keep more moisture in the monsoon for condensation further inland." Such plans are not new. For example, G. A. Thompson proposed "A plan for converting the Sahara Desert into a sea" in the 10 August 1912 issue of *Scientific American* (p. 114). Obviously, more schemes will be advanced.
42. H. Landsford, *Bull. Am. Meteorol. Soc.* **54**, 658 (1973).
43. W. D. Sellers, private communication.
44. E. LeRoy Ladurie, *Histoire du Climat depuis l'An Mil* (Flammarion, Paris, 1967).
45. We wish to acknowledge the encouragement of G. Kukla, organizer of the AAAS symposium "To Feed the World" (San Francisco, 27 February 1974), at which this paper was originally presented. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Viral Infection and Host Defense

Many aspects of viral infection and recovery can be explained by the modulatory role of double-stranded RNA.

William A. Carter and Erik De Clercq

Current interest in double-stranded RNA's (dsRNA's) takes on many forms. It ranges from physicochemical studies of their structure, through descriptions of the large diversity of cellular reactions brought about by these molecules, to studies of events triggered at the level of the intact animal.

We attempt in this article to develop a perspective on the heterogeneity of reactions provoked by dsRNA in biological systems. We describe how chemical lesions (bond breakage, unpaired bases) in the double-helical structure can modulate or abort biological function. Finally, we submit for consideration a hypothesis that dsRNA is both the molecular mediator of much of the morbidity and cellular damage associated with cytolytic viral infection, as well as a crucial molecular trigger that stimulates many of the organism's defenses to viral infection. By defining this dynamic role of dsRNA, we hope to signal new experimental inquiry which may permit a more detailed analysis of events at the molecular level, which until now have been described at the microscopic level as "extreme tissue damage probably due to a virus."

Before we proceed with development of ideas on the role of dsRNA in viral infection, it should be recalled that dsRNA is generally considered as not being a regular constituent of the eukaryotic cell. This view is clearly correct in a quantitative sense, although it may require some revision. For example, it has been shown that heterogenous nuclear RNA contains double-stranded regions (*1*). Recently, dsRNA from nuclei of HeLa cells has been isolated (*2*) and shown to have molecular weight in excess of ~25,000. It is postulated that dsRNA may interact with an initiation factor thought to be necessary for messenger RNA (mRNA) translation (*3*); a helical region greater than 20 base pairs seems to be involved in this recognition. The amount of dsRNA in ascites tumor cells appears to be under control of a specific nuclease (*4*), and thus the extent and the rate of translation could be regulated by this mechanism. Such evidence supports the view that dsRNA may have a regulatory role in protein synthesis within mammalian cells.

Interferon Induction by dsRNA

Many specialized cellular functions are altered in cells exposed to dsRNA. One of the most characteristic functions triggered by dsRNA is the production of interferon. Various dsRNA's of both biological and synthetic origin have been shown to stimulate interferon production:

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