AD 675950

CHANGING CLIMATE

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September, 1968

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P-3933

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ABSTRACT

The following questions are discussed:

1. Is global climate changing?
2. What is the pattern of global climatic change?
3. What causes global climate to change?
4. Is man's activity inadvertently influencing global climate?
5. What are the possibilities for purposefully influencing global climate?
6. What interest and competence have been shown by nations of the world in global climate control?
7. What can be done to speed progress?

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This summary statement was prepared as an individual contribution to a more comprehensive RAND review of weather and climate control.

I. IS GLOBAL CLIMATE CHANGING?

The climate of a particular region is determined by a number of relatively static factors such as elevation, latitude, topography, and type of surface, and also by the properties of the air which passes over it. The dynamic factor which causes weather changes is the circulation of the atmosphere. Variations in the mean behavior of the atmospheric circulation over a period of years constitutes a variation of climate.

Substantial, worldwide changes of climate do occur, even within the span of a few decades, and have been described by many investigators (Mitchell, 1963; Willett, 1965; Lamb, 1966; Rubinstein and Polozova, 1966). The data clearly show that the general vigor of the global atmospheric circulation undergoes significant variations, with associated latitudinal shifts of the main zonal currents and changes in the nature of their disturbances. Variation in the global circulation pattern is the common factor which makes possible a coherent interpretation of climatic data from all parts of the earth.

For example, during the first three decades of this century the trend was toward growing strength of the northern hemisphere zonal circulation, northward displacement of polar fronts in both the atmosphere and the ocean, northward displacement of the ice boundary, weaker development of blocking anticyclones over the continents, more northward cyclone paths and pronounced aridity of the south central parts of North America and Eurasia (the dust bowl). Conversely, recent decades have exhibited opposite trends: weakening zonal circulation, southward shifts of ice boundary and cyclone paths, and substantially increased rainfall in the south central parts of the continents.

1968, thus far, has underscored these trends. Icelandic fishermen suffered great losses due to the most extensive sea ice in the last 60 years, while phenomenal wheat yields from the central plains, both North American and Eurasian, have pushed wheat prices to a 26-year low. Even India produced so much wheat that its storage facilities were fully utilized, blocking the acceptance of U.S. surplus shipments. (Although as recently as Christmas, 1967, it was widely

predicted that millions of Indians would die of starvation in 1968.) These cases illustrate that our complex pattern of human activity is sensitive to relatively small variations in climate. But the range of variation of global climate is enormous. Less than 20,000 years ago the Pleistocene ice sheet still covered North America from the Atlantic to the Pacific with a thickness of up to two miles. The last major ice sheet disappeared from Scandinavia about 8000-7000 BC, while in North America the ice retreated at an even later date. During the period of ice retreat and somewhat after, rainfall in the Mediterranean area and perhaps over much of the hemisphere was less than at present, possibly due to cooler oceans. The post glacial warming culminated in the "climatic optimum" of 4000-2000 BC, during which world temperatures were 4-5°F warmer than they are now and rain was much more plentiful in North Africa, where the Egyptian civilization was developing.

The decline from the warm optimum was abrupt from about 1000 BC, with cooling continuing to about 400 BC. This was a period of maximum North African rainfall and rapid development of human activity, partly induced by climatic stress. For example, a period of stormy climate in the North Sea area at about 120 BC set the Teutonic peoples on the move. By this time renewed warming had set in which continued until the "secondary climatic optimum" of 800-1000 AD. This period was characterized by a relatively dry, warm and storm-free North Atlantic and was the time of the great Viking colonization of Iceland, Greenland and Newfoundland. The decline, from about 1300 AD with one partial recovery about 1400-1550, continued until about 1750, culminating in the "little ice age" of 1550-1840. During this period Arctic pack ice advanced in the North Atlantic and the Greenland and Newfoundland colonies were extinguished.

II. WHAT IS THE PATTERN OF GLOBAL CLIMATE CHANGE

Only during the last century have we begun to observe our global ocean/atmosphere system in enough detail to discern some of the patterns of climatic change, but even today, our ability to observe the essential elements of the global system is far from adequate.* However, some of the characteristic features of global climatic changes are now emerging, and have been described by several authors, most completely by Lamb (1966a). The pattern is so complex and so much influenced by various ocean/atmosphere feedback interactions that no investigator has thus far put forward a plausible physical explanation, and it has only been possible to describe in increasing detail how the global system changes. In piecing together this picture the connecting factors that make possible a rational description of global climate are the general vigor of the global atmospheric circulation and to an increasing extent, the variation of sea surface temperatures in response to changing atmospheric circulation.

Since the "little iceage" of 1650-1840, which climaxed the cooling trend from about 1300, a new warming trend predominated which seems to have reached a climax in the 1920's, followed by cooling since about 1940, at first irregularly but then sharply since about 1960. The periods of general warming were accompanied by increasing vigor of the westerly zonal circulation in both hemispheres, bringing a more maritime climate to the continents, more northerly cyclone tracks and a pronounced warming of the Arctic. (From 1890 to 1940 the mean thickness of Arctic pack ice decreased by more than 1/3 (Ahlmann, 1945). Since about 1940 the reverse pattern has occurred, with weakened zonal circulation, greater development of blocking anticyclones over continents in winter, more variable and southerly cyclone paths, and a colder Arctic.

Neither the warming trend nor the cooling trend proceeded smoothly; on the contrary, there seem to have been critical thresholds at which sudden changes occurred. Some of the characteristics of these sudden changes are now beginning to be revealed.

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*For example, sea surface temperatures and sea ice extent.

During the warming from 1840 to 1930 a sudden change seems to have occurred about 1893-95, characterized by sharp increase in zonal westerlies and a concurrent decrease of rainfall associated with the intertropical convergence zone (Kraus 1954, 1955, 1956, 1959, 1963). Conversely, after the gradual and variable cooling since 1940, a sudden decrease in westerly circulation occurred about 1961-63, with a concurrent increase of rainfall in the intertropical convergence zone. At the same time the intertropical convergence zone seems to have narrowed and increased in zonality (Lamb, 1966d). Associated with these changes in the intensity of the main zonal circulation, there has been a shift in the mean longitudinal positions of the climatic troughs and ridges: eastward with growing wind speed, westward with weakening wind speed, accompanied by an associated major displacement of rainfall and drought patterns (see Fig. 10 from Lamb, 1966d). The economic consequences of these shifts are enormous, as was noted at the beginning of this paper in reference to India's 1968 wheat surplus.

The greatest obscurity in the observed behavior of the atmosphere is in the southern hemisphere. No reliable index has been found for the strength of the southern hemisphere trade winds and even the indices of zonal westerlies are suspect, coming from either New Zealand or Chile and not extending far enough south. Temperature patterns for the 80 per cent of the southern hemisphere covered by oceans are nonexistent. Even since the IGY, year to year variations in the sea ice covering 13 per cent of the southern hemisphere ocean in winter are largely unknown. However, the meager data that are available strongly suggest that the "worldwide" warming and cooling referred to above extended only to about 60°S, beyond which the secular trends were in the opposite direction (Lamb 1966c) (Fletcher, 1968).

III. WHAT CAUSES GLOBAL CLIMATE TO CHANGE?

No one has been able to explain why such climatic variations occur. They seem to be associated with variations in the vigor of the whole global atmospheric circulation, but why the global system varies is still a mystery. It follows that the fundamental problem in the study of climatic change is the development of a quantitative understanding of the general circulation of the atmosphere; and, since three-fourths of the heat which forces the atmospheric motion comes by way of the ocean surface, a quantitative understanding of oceanic heat transport and ocean/atmosphere heat exchange is especially vital.

Such an understanding should begin with the planetary distribution of heat loss and gain by the atmosphere and ocean, and by using the fundamental physical laws (embodied in the classical equations of motion and thermodynamics) should enable us to predict the global distribution of temperature, pressure, motion, water vapor, clouds and precipitation, together with resulting moisture and heat transports. In principle, such an analytic approach is straightforward and was outlined by V. Bjerknes in 1904 (Fletcher, 1965, p. 149). In practice, however, there are enormous difficulties. The late John von Neumann, who led the modern assault on the problem of mathematical simulation of the atmosphere has been quoted as saying that "forecasting the weather for more than a day or two in advance is the most complicated and difficult physical and mathematical puzzle yet proposed or even thought of" (Thompson and Roberts, 1967).

Nevertheless, with the development of modern computer technology, rapid progress is being made. Already it is becoming possible to simulate mathematically certain large-scale processes in more detail than we observe them in nature. (For a survey of the background and present status of atmospheric modeling, see Gavrilin, 1965.)

This progress toward simulating atmospheric dynamics calls for better understanding of the processes of atmospheric heat losses and gains which force the motion of the real atmosphere. Although the general atmospheric circulation is forced by an uneven distribution

of heating between the equator and the poles, variations in equatorial heating and variations in polar cooling are poorly understood and little studied, largely because of the paucity of relevant data over the oceans.

Nevertheless, it has been discovered that significant anomalies of ocean/atmosphere heat and moisture exchange do occur and that these anomalies are closely related to variations in the dynamical behavior of the atmosphere.

The first ocean area to receive detailed study was the North Atlantic (Sandstrom, 1932) and these studies have since been extended by many investigators to encompass the whole Atlantic (Shishkov, 1962; Bjerknes, 1964; Sorkina, 1965; Namias, 1966).

In recent years the emphasis of leading investigators has shifted to the Pacific, where even larger anomalies of ocean/atmosphere heat exchange have been found to occur, both in the equatorial zone (Bjerknes, 1958, 1959, 1960, 1966, 1968) and in the mid-latitudinal North Pacific (Wyrtki, 1966) (Namias, 1968).

For example, one very influential ocean/atmosphere interaction which is subject to large and sudden anomalies is associated with the zone of cold water at the equator, which is caused by the opposite deflection of surface water north and south of the equator in response to the easterly trade winds. In the eastern Pacific, the temperature difference between this upwelling water and the warm waters on either side is normally several degrees and extends for several thousand miles. In the Indian Ocean, the 1963-64 expedition found a cold equatorial tongue nearly 10° colder than surrounding waters. ($28^{\circ}C$-$18^{\circ}C$) (Lamb 1966d)

During some years these cold tongues weaken or vanish as the equatorial trade winds wane. Bjerknes has documented several such cases for the Pacific, showing that the resulting variation of evaporation and subsequent condensation influences the circulation of the whole northern hemisphere. Similar studies for the Indian Ocean have not yet been conducted due to the lack of data, but it seems likely that similar processes are associated with the phenomenal rise of East African rainfall since 1961-63. Indeed, the frequency of such

occurrences may be closely connected with the abrupt changes in the global system since 1961-63. (Lamb, 1966d)

Unfortunately, we do not know why the equatorial trade winds wane. Presumably this has to do with the strength and position of the southern hemisphere oceanic anticyclones, the strength of the southern zonal westerlies and the longitudinal shifts of mean troughs and ridges. There is growing evidence that variations of the northern hemisphere circulation are related to variations of the much stronger southern hemisphere circulation, but the basic cause of the planetary variation is still a mystery.

Impressive statistical correlations between various indices of climatic change and various indices of solar activity have been presented by many investigators (Fairbridge, 1961, Rubinshteyn, 1966), but no one has been able to advance a physically-plausible cause and effect explanation. Variations in the solar "constant" are usually judged to be too small to account for the relatively large observed variations of global climate (Sawyer, 1966). As a result, much attention has been directed towards searching for mechanisms by which upper atmosphere processes, triggered by small changes in the energy from the sun, can in turn influence much more energetic tropospheric processes. However, a better understanding of ocean/atmosphere interactions may reveal that feedback processes can amplify the effect of small solar variations to produce large changes in the behavior of the planetary system. One such "thermal lever" is the variable extent of ice on the ocean. (Fletcher 1965, 1968). The presence of ice on the sea effectively prevents heat transfer from ocean to atmosphere in winter, thus forcing the atmosphere to balance the heat lost to space. A decrease in solar radiation tends to cause cooling, which causes ice extension, which in turn cools the atmosphere more and causes more ice growth and stronger thermal gradients. The causes and effects are self reinforcing, providing "positive feedback." How far such a process must go before triggering other instabilities in the ocean-atmosphere system, such as the sudden variation of equatorial temperature described above, cannot be judged at this time. Clearly, there are many complex feedback processes, both positive and negative, in the

ocean/atmosphere "climate machine" and many thresholds beyond which the direction of the feedback can change. For example, suppose that the warming of the Arctic, which by 1940 had greatly reduced the pack ice thickness, had continued. As the ice receded farther in summer and the thinner ice was more fractured in winter, evaporation would greatly increase, thus salinifying and cooling the surface waters and decreasing the vertical stability of the upper layers of the ocean. If this process continued to the point of destroying the present strong stratification of ocean surface layers and inducing deep convection, then refreezing at the surface would be impossible until the whole water column had cooled to freezing temperature -- a process which would take many years at the least. After the whole ocean had cooled to the freezing temperature, additional cooling would refreeze the surface, thus recreating surface stratification and reformation of surface ice, the initial condition. Thus a "threshold" exists in both directions.

Many other examples of "feedback processes" and thresholds, from small scale to planetary scale, could be given. Some need to be systematically evaluated quantitatively, by field observation, by physical explanation, and by laboratory simulation (using mathematical models of atmospheric and oceanic circulation). Possibly such feedback processes can amplify the climatic effects of variations in solar "constant" or variations in atmospheric transparancy caused by volcanic eruptions. Evidence that atmospheric dustiness is the primary cause of climatic variations has been presented by Davitaya (1965) and Budyko (1967ab).

As a final comment on causes of climatic change, the present lack of understanding can perhaps be underscored by noting that even the variable rotation rate of the earth on its axis (due to shifting mass in the molten core) cannot be excluded as possible cause. In fact, impressive statistical correlations relating variable rotation speed with secular climatic changes have been presented (Maximov, 1954). This line of investigation was not considered very promising by most meteorologists, but the different behavior of atmospheric circulation since the sudden slowing down of the Earth's rotation in 1961 by 1 millisecond per day, has created new interest in the problem.

IV. IS MAN INADVERTENTLY INFLUENCING GLOBAL CLIMATE?

Whether human activity has been a significant cause of the large climatic shifts of the past century is a question which cannot yet be answered with any confidence. The complexities of global climate are still too poorly understood so assess the dynamical response of the system to a given change, yet it is the dynamical response of both the ocean and the atmosphere that primarily determines climate. However, many investigators have argued that the effects of man's activities are already significant, or even dominant, in changing global climate. The influencing factors most frequently suggested are carbon dioxide pollution, smog (dust) pollution and heat pollution. The physical arguments advanced have to do with the effects of these pollutants on the heat balance of the atmosphere.

Carbon dioxide is one of the three important radiation absorbing constituents in the atmosphere (along with water vapor and ozone). There is no doubt that its concentration has been increasing in the last century, apparently by some 10-15%. The physical effect of a greater CO_2 concentration is to decrease the radiative loss to space. (Due to the fact that the radiation comes from a higher and hence cooler level in the atmosphere.) Thus, an increase in CO_2 increases the "greenhouse effect" and causes global warming. Many investigators have suggested that the warming since 1900 was due to just such an increase in CO_2. Callendar (1938, 1961) and Plass (1959) estimate that a warming of almost $1^{o}F$ during the last century could be attributed to this cause, and this is comparable to the warming that that did occur. It is further estimated that, by the year 2000, a further warming of $3^{o}F$ could be caused by CO_2. Other authors have estimated an even greater warming Nothwithstanding these arguments, the sharp global cooling of the past decade indicates that other factors are more influential than increasing CO_2. For example, Moller (1953) estimates that a 10% change in CO_2 can be compensated by a 3% change in water vapor or 1% change in mean cloudiness. Moreover, the oceans have an enormous capacity to absorb CO_2, which also varies with temperature; that is, colder oceans can store more CO_2. Thus, warming oceans could

also be a primary cause of increasing CO_2 in the atmosphere. In summary, it appears that, other factors being constant, CO_2 from human activity could cause important changes of global climate during the next few decades. But, of course, other factors are not constant, and in recent years have apparently been more influential than the CO_2 increase.

With regard to heat pollution, Budyko (1962, 1966) points out that, although the yearly production of energy on earth is now only about 1/2500 of the radiation balance of the Earth's surface, it would become equal to the surface radiation balance if compounded annually at 10% for 100 years or 4% for 200 years. (The present growth rate is about 4%, which is a doubling each 17 years). From these numbers we may conclude that sometime during the next century heat pollution, like CO_2, will indeed become important on a global scale. By then we must learn to compensate for it. But for the time being, and for the next few decades, it will be insignificant on the global scale.

Budyko (1966) also considers forest belts, irrigation projects, swamp drainage and creation of reservoirs. Such projects can greatly influence the climate of a local region, but none seem likely to be significant compared to global processes.

One of the most rapidly increasing man-made forms of atmospheric pollution is smog, which includes all forms of industrial pollution. Bryson (1968) suggests that there has been a turbidity increase of 30% per decade over Mauna Loa Observatory, which is far from all sources of pollution. Bryson further argues that a more turbid atmospheric transparency, even by only 3 - 4%, could change the global mean temperature by $0.7^{\circ}F$, an amount comparable to changes of the last century. He believes that increasing global air pollution, through its effect on the reflectivity of the earth, is currently dominant over CO_2 increase and solar variation, and is responsible for the temperature decline of the past decade or two. If Bryson's interpretation is correct, mankind faces an immediate and urgent problem of global climate control, for smog production is increasing everywhere at an exponential rate and no means of curbing this increase are in sight.

Still another form of growing pollution, and one whose possible effects have been little studied, is the creation of cirrus cloudiness

by the exhaust products of high flying aircraft (vapor trails). Increased cloudiness of any form tends to increase the reflectivity of the earth and, according to Bryson's calculations, a 1% increase in mean albedo would cool the earth by $3^{o}F$. However, it may be noted that increased cloudiness at high levels greatly reduces radiative loss to space, and this effect would warm the earth. Thus, the effect of more or less cloudiness is very great, but the direction of the influence depends on the type and height of the clouds and on whether they are in a dark or sunlit region of the earth.

Still other forms of pollution have not as yet been evaluated at all for their possible influence on climate. For example, fuel expended by ships comes to about 10^9 tons per year. Assuming 5% incomplete combustion, some 50 million tons per year are released as pollutant. Presumably, that fuel which is spread on the sea is consumed by bacteria, but it is unclear just how quickly this takes place. Where an oil film is allowed to persist, it influences the heat balance by not only reducing evaporation and turbulent heat flux, but also lowering the radiative emissivity of the surface.

From the foregoing considerations, we may conclude that man is probably inadvertently influencing global climate at the present time. Certainly several products of man's activity are theoretically influential enough to do so within a few decades. However, there are so many variables and degrees of freedom in the global system that specific cause and effect estimates in this regard are very uncertain.

V. WHAT ARE THE POSSIBILITIES FOR PURPOSEFULLY INFLUENCING GLOBAL CLIMATE?

Theoretical perspectives for influencing large scale atmospheric circulation have been formulated by Yudin (1966). Some of his conclusions can be summarized as follows:

a. In order to divert air movement over a given region, it is theoretically most effective to apply energy evenly over broad portions of the air mass. This is necessary in order to minimize the dissipation of energy by parasitic acoustical and gravity waves. In other words, the partitioning of the applied energy among the various scales of atmospheric motion depends on the suddenness with which it is applied.

b. To influence the field of motion, in addition to Criterion (a), it is also desirable to avoid intermediate links involving conversion of thermal energy to potential energy, then to kinetic energy. More direct methods must be found.

c. In theory, it should be possible to change the velocity field with much less energy than would be necessary to change the temperature field or pressure field. Direct action is much more effective than thermal action.

d. Investigation of conditions of stability for atmospheric perturbations indicates that, under certain conditions, a small energy addition might lead to large changes in the further course of a process. Emphasis should be placed on identifying critical "instability points" in the natural development of cyclones.

e. Theoretically, action on the field of the ageostrophic wind and particularly on the vertical component of the ageostropic wind should produce the largest influence for the energy expended.

f. In connection with the possibility of steering cyclones, Yudin stresses that only slight deflections of the wind from the geostropic are associated with much faster movement of cyclone centers.

g. In connection with influencing the intensity of cyclones, Yudin calculates that "by creating a descending movement with a velocity of 3 cm/sec at the upper boundary --, we can essentially weaken the intensity of a cyclone in eight hours."

These brief criteria clearly identify one difficulty associated with large scale weather modification, namely, that the theoretically most effective approaches all involve actions that we do not know how to produce efficiently. On the other hand, various ways of influencing the thermal losses and inputs to the atmosphere, although theoretically inefficient from the viewpoint of immediate dynamical consequences, are much more achievable with present technology. For example, it has already been noted that the creation or dissipation of high cloudiness has an enormous influence on the heat budget of the atmosphere and of the surface. Moreover, under certain conditions, only one kg of reagent can seed several km^2. It is estimated that sixty C-5 aircraft, operating from Eielson AFB and Thule AFB could deliver 1 kg per km^2 per day over the entire Arctic basin ($10^7 km^2$).

Thus, it is a large but not impossible task to consider seeding such enormous areas. Assuming that such seeding were effective in creating or dissipating clouds, it is of interest to estimate the effect of such cloudiness on the heat budget of the surface/atmosphere system. According to Vowinkel and Orvig (1964), the presence of average cloudiness over the Arctic in July decreases the radiative loss to space by about 350 billion cal/km^2/day from what it would be without clouds. For comparison, 100% cloud tops at 500 m would decrease radiative loss by only 50 billion cal/km^2/day while 100% cloud tops at 5,000 m would decrease radiative loss by about 1,000 billion cal/km^2/day. These numbers demonstrate not only the enormous thermal leverage that might be exercised by influencing mean cloudiness, but also the enormous range of influence that might be possible, depending on cloud type, height, and its influence on the regional heat budget. This conclusion is further underscored by noting that mean monthly values of radiative loss at the surface have been observed to vary by more than 100% in different years at some Arctic stations.

Similarily, it may be noted that, under certain conditions, influencing the surface albedo of Arctic pack ice is not beyond the capability of present technology. Since the presence of sea ice effectively severs the intense heat flux from ocean water to cold atmosphere, regulating the extent of sea ice is still another possible way of exercising enormous thermal leverage on patterns of thermal forcing of atmospheric motion (Budyko, 1962) (Fletcher, 1965, 1968).

Influencing the temperature of the ocean surface over extended areas by changing the courses of certain ocean currents in various ways has also been proposed. (Wexler, 1958) (Rusin and Flit, 1962) (Borisov, 1959, 1967). These schemes involve large but not impossible engineering efforts. The principle difficulty, however, is that present understanding of ocean dynamics is too rudimentary to reliably predict the effects of such projects and, even if this were possible, the dynamical response of the atmosphere to the new pattern of heating could not be predicted.

These various examples are enough to demonstrate the following essential conclusions: (1) It does appear to be within man's engineering capacity to influence the heat loss and gain of the atmosphere on a scale that can influence patterns of thermal forcing of atmospheric circulation. (2) Purposeful use of this capability is not feasible because present understanding of atmospheric and oceanic dynamics and heat exchange is far too imperfect to predict the outcome of such efforts. (3) Although it would be theoretically more efficient to act directly on the moving atmosphere, engineering techniques for doing so are not presently available. (4) The inadvertant influences of man's activity will lead eventually to catastrophic influences on global climate unless ways can be developed to compensate for these undesired effects. Whether the time remaining for bringing this problem under control is a few decades or a century is still an open question. (5) The diversity of thermal processes that can be influenced in the atmosphere, and between the atmosphere and ocean, offers promise that, if global climate is adequately understood, it can be influenced for the purpose of either maximizing climatic resources or avoiding unwanted changes. For example, to avoid undesired planetary warming,

ways must be found to drain additional heat to space. Regulating cloud cover, as suggested in an example above, is one possible way of approaching this problem.

VI. WHAT INTEREST AND COMPETENCE IN GLOBAL CLIMATE CONTROL HAVE BEEN SHOWN BY NATIONS OF THE WORLD

Only the U.S. and the USSR have expressed serious interest in the problem of influencing global climate.

In the U.S., this expression has taken the form of statements by the U.S. National Academy of Sciences (1966) and the National Science Foundation (1965), pointing out the possible necessity for influencing global climate and commenting on the scientific feasibility of doing so. The only formal research program to date has been the NSF funding program for "Weather Modification" which has for several years included some basic work on climatic change and possible climate control.

In the USSR, both governmental and scientific interest has been more evident. A conference on climate modification was held in Leningrad on 25-28 April 1961 under the sponsorship of the three institutions most closely concerned with the problem -- The Main Geophysical Observatory, Leningrad, The Institute of Applied Geophysics, Moscow, and the Institute of Geography, Moscow (JPRS 24512). At this conference, the Chief of the Hydrometeorological Service, Ye K. Fedorov, estimated that some 5 to 10 years would be required to adequately define the problem. (It is now seven years later and as yet the problem has not been adequately defined). Fedorov also stressed investigation of ways to influence heat exchange between the atmosphere and the surface as the most promising approach for influencing large scale processes.

Scientists of the various Institutes also reported on various aspects of climate control investigation. At the Institute of Applied Geophysics, Moscow, this work is led by A.N. Gusev, Director of the Climate Laboratory, and has emphasized the development of a more adequate theory of global climate, including attempts to develop models of global circulation. At that time, emphasis was on mechanical and electrical analogue models. In recent years, emphasis is shifting to mathematical models as computer facilities grow in power.

At the Institute of Geography, Moscow, emphasis has been on analysis of observed changes of climate and their possible causes. The Director, I.P. Gerasimov, has stressed that future modification of climate should not be undertaken without an understanding of such events in the past, including the causes of such large variations as the Quaternary ice ages. B.L. Dzerdzeevskii at the Institute of Geography has led work on the analysis of atmospheric circulation types and their relation to observed solar changes.

At the main Geophysical Observatory, Leningrad, emphasis on possible climate modification has the longest history and represents the greatest level of effort. Since coming to office in 1954, Director M.I. Budyko has stressed study of the heat balance of the surface/atmosphere system over the earth. A special series of studies have been directed toward the possible removal of the ice cover from the Arctic Ocean. It was concluded that the Arctic sea ice, once removed, would not recur. Instead, a new climatic balance would be established in which sufficient heat would be furnished to the Arctic Ocean to compensate its winter losses. Computations have been made to determine the climatic characteristics of Eurasia and North America under these conditions. However, such computations have been greatly handicapped by the unavailability of an adequate mathematical model or the computer power to simulate global climatic behavior under specified boundary conditions. Summaries of this work were presented at a U.S. symposium in 1966 (Fletcher, 1966).

In recent years, the main computing center of the new "Science City" at Novosibirsk has been assuming a growing leadership in the development of mathematical models of global climate. The Director, G.I. Marchuk, has maintained close contact with U.S. work by extended visits. (1965, 1967, 1969).

Also, the Institute of Oceanography, Moscow, is sponsoring a growing capability emphasizing mathematical models of oceanic and atmospheric circulation. The Director, A.S. Monin, is a dynamic meteorologist and has stressed the influence of ocean/atmosphere interaction on global climate. The extended U.S. visit of his colleague, B. L. Gavrilin, during 1968 is a part of this long range program.

An organizational framework for governmental supervision of these programs was established in 1962 when a Special Council on Modification of Meteorological Processes was established under the State Committee on the Coordination of Scientific Research Work of the Soviet Council of Ministers. The first meeting of this group was held in Leningrad 11-13 June 1962, where sixteen reports were presented (JPRS:24512). We have no recent information on the activities of this group.

Budyko (1962) reports that "the new program of the Soviet Communist Party, adopted at the 22nd Party Congress, lists the development of climate-control methods among the most urgent problems of Soviet science." (See also, Materials of the 22nd Congress of the Communist Party of the Soviet Union, Moscow 1961, p. 415) (Zikeev and Doumani, 1967).

In general, Soviet work has been most severely handicapped by the lack of computer power comparable to that available in the U.S. However, all of the interested Soviet institutes have demonstrated great emphasis on theoretical work which will contribute to rapid progress as more powerful computers become available. They have also maintained close contact with U.S. groups developing models of atmospheric circulation, maintaining visiting scientists with them much of the time.

In addition, Soviet agencies have been investing great efforts in field observations, especially in high latitude oceanic regions. The following announcment by the Novosti Press Agency is indicative of these efforts. (Arctic, Vol. 21, No. 2, 1968)

> "A program of investigations into the mutual influence of the oceans of the world and the atmosphere has been mapped out in the Soviet Union. These studies are aimed at long-term weather forecasts, the elucidation of the reasons for climatic fluctuations, forecasts of the ice regime in the Arctic seas, and a better organization of fishing, and hunting sea-animals.
>
> Concerning the natural experiments suggested by the Arctic and Antarctic Scientific Research Institute (whose program has been discussed in the U.S.S.R. Geographical Society), the head of the Hydrological Regime Sector, Yevgeny Nikiforov, M.Sc. (Geography) said that a vast territory will be subjected to observations conducted according to special techniques. The natural experiment zone will

embrace the northern arts of the Atlantic and the Pacific, the Arctic Ocean, and the Norwegian, Greenland, and Barents seas.

The investigations will be conducted from research vessels and planes equipped with special scientific instrumentation and automatic meteorological stations. At the same time, the natural experiment will extend over territories of the continents adjacent to the oceans and seas. During these observations it is planned to use the entire network of meteorological stations, and the North Pole drifting stations; special high-latitude expeditions will be launched."

The decade of the 1970's promises to be a period of rapidly growing international cooperation and activity directed toward study of global atmospheric circulation. The planned Global Atmospheric Research Program (GARP) grew out of a proposal of President John F. Kennedy to the U.N. General Assembly in 1961. General Assembly Resolution 1721 (XVI) recommended joint action to "study basic physical processes that affect climate and that would be involved in large scale weather modification."

U.N. Resolution 1802 (XVII) 1962 initiated a long series of planning conferences under the auspices of the World Meteorological Organization (WMO), the International Council of Scientific Unions (ICSU), and the International Union of Geophysics and Geodesy (IUGG). The most recent study conference met at Stockholm in June 1967 to formulate detailed scientific requirements. The first large scale observation program will probably be in 1973. Thus far, American scientists have played the leading roles in these activities.

VII. WHAT CAN BE DONE TO SPEED PROGRESS?

With environmental problems, it is convenient to think of progress in four stages -- observation, understanding, prediction, and control. We must observe how nature behaves before we can understand why, we must understand before we can predict and we must be able to predict the outcome before we undertake measures for control. Much progress is needed in all four areas in order to achieve the degree of control over climatic processes that is becoming necessary.

In the past, progress has been severely limited by several factors that are now changing rapidly.

One factor was limited observations. No more than about 20% of the global atmosphere was observed at one time, and that very incompletely. With the advent of satellite observing systems some quantities can be observed over the entire planet every day. This observational breakthrough makes possible the synoptic surveillance of the entire global system and the sophistication of the observations that can be made by satellite is rapidly increasing. The processing and dissemination of this vast new pool of data presents many problems, which are gradually being resolved by the National Environmental Satellite Center. (Brister, 1967, 1968).

Synoptic observations of the global system have further emphasized the necessity of observing certin typical regions in great detail for a limited period in order to understand the heat exchange processes taking place and their influence on the atmosphere and the ocean. This is especially important in regions which play an important role in the thermal forcing of atmospheric and oceanic circulation, and where large year to year variations can occur. In the equatorial heat source region, variations in the intensity of the tropical convergence zone seem to be associated with changing global climate. In the two polar heat sink regions, variations in extent of ice cover on the ocean also seem to be associated with changing global climate. In all cases, both the causes and the effects of these variations are obscure.

The equatorial problems are receiving increased attention in recent years, and several field observational programs have been conducted there: the "Indian Ocean Experiment" of 1964, the "Line Island experiment" of 1966, the "Barbados Experiment" of 1968, and the planned sequels to these experiments, "TROMEX" in 1969 and a later "Marshall Islands Experiment."

Similar planning for regions of large heating anomalies at high latitudes is needed but has not yet gotten under way. One region of prime importance is the Weddell Sea sector of the Southern Ocean, which is thought to be the source of most of the bottom water of the world ocean. A very limited two year field program began in 1968, aimed at preliminary measurements of bottom water runoff. To learn how this important region influences the global atmosphere and the world ocean, the program should be expanded to include year-round quantitative observations of the patterns of ocean/atmosphere heat exchange and should be extended to be concurrent with large scale international efforts to observe the behavior of the southern hemisphere atmospheric circulation. (Such as the "Eole Experiment" in 1970 and the tentative "GARP" experiments in 1973 and 1976.) With regard to the northern heat sink region, formulation of needed field measurements was a prime subject of a "Symposium on the Arctic Heat Budget and Atmospheric Circulation" sponsored by NSF in 1966. Detailed recommendations are included in the proceedings (Fletcher, 1966).

A second factor limiting progress has been the nature of the problem. An adequate theoretical basis has not as yet been developed for explaining the interactions of the global heat engine and for accounting for observed changes in climate. Causal relationships have been obscured by the multitude of factors operating and problems for investigation have often been ill-defined. Research methods are often painfully slow and frustrating and thus appear less attractive to graduate students than the more direct methods of experimental sciences; observation of physical behavior, formation of a hypothesis, deduction of consequences from the hypothesis, and the testing of deductions by physical experiment. These limitations are also changing rapidly, for the rapid increase in computer power, coupled with the parallel development of mathematical models of atmospheric and oceanic circulation,

promise powerful experimental tools for testing hypotheses and causal relationships. An inevitable result will be the development of a more sophisticated theory to explain climatic change which, in turn will trigger an avalanche of "climatic experiments" testing the predictions of the improved theory of climate.

Thus, not only is "observation" in the throes of a technological breakthrough, but also "understanding" and "prediction." For these reasons, relatively rapid progress over the next decade is inevitable.

This process is already under way, but the rate and direction of progress will obviously be influenced by the scale and organization of the resources invested, both human and material. At present, there are three main groups developing atmospheric circulation models (ESSA, NCAR, UCLA). There are at least two substantial groups investigating the causes of climatic change (MIT, University of Wisconsin), and additional groups investigating global heat engine features that are both influential and subject to large variations (Arctic heat exchanges -- McGill, University of Washington; Antarctic heat exchanges -- CSIRO, University of Wisconsin; Equatorial heat exchanges -- McGill, Florida State, University of Miami). It would be desirable to bring the concerted capabilities of these and other groups to bear within a systematic program of climate research utilizing numerical experiments based on theoretical analysis and field observation. Ways of furthering this aim should be systematically explored.

It is clear that the means are presently at hand to support rapid progress in observation, understanding, and prediction. But, what about control?

It must be emphasized that purposeful control of climatic processes will not be possible until a much more adequate climatic theory is developed. On the other hand, it is presently possible to identify and investigate certain potential techniques for influencing climatic processes.

The example of cloud seeding over the Arctic basin was cited earlier and there are many more ways in which heat exchanges might be influenced on a large scale, such as influencing the albedo of the

surface or the radiative properties of the atmosphere (Rusin, 1962 - Fletcher, 1965 - Budyko, 1962). Such techniques should be systematically evaluated, and new ones discovered. In general, such tests must be conducted under natural conditions and be designed to trigger cumulative effects on natural heat exchanges. Nature sets a limit on the rate of such experimentation, as the annual cycle occurs only once a year. It can be anticipated that when rapid experimental progress becomes urgent this limitation will be severely felt. Meanwhile, it would be wise to inititate a small but systematic program of field evaluation of such potential techniques for large scale weather modification.

Also, it may be noted that an understanding of contemporary and future climatic changes can hardly be achieved without understanding the large climatic changes of the past. Defining the patterns of these changes is a way of observing nature's own "climate control experiments." Yet, the collection and systematization of paleoclimatic evidence has been both meager and uncoordinated in the U.S. There is no U.S. institutional counterpart to, say, the Main Geophysical Observatory in Leningrad or the Institute for Geography in Moscow. There has been no coordinated effort comparable to that led by Lamb at the British Meteorological Office. It is not suggested that these institutional efforts be emulated in the U.S., but rather, that the pace of the U.S. investigation could be increased by a recognition of the importance of such work by U.S. funding agencies and by a modest increase in the level of support.

Finally it must be emphasized that management of climatic resources is a problem shared by all nations. The global ocean/atmosphere is a single interacting physical system, in which an action anywhere may influence behavior everywhere. We are rapidly approaching the time when progress toward learning how to manage global climate will be proportional to the purposeful investment of scientific efforts. Coordination of these efforts is in everyone's interest.

REFERENCES

Ahlmann, Hans W., 1945: The Organization of Soviet Arctic Research, Polarboken, Stockholm, p. 32.

Bjerknes, J., 1958: "Related Fluctuations of Trade Winds and Northern Climates," Geophysica Helsinki, Vol. 6, No. 3-4, pp. 169-177.

-----, 1959: "The Recent Warming of the North Atlantic," The Atmosphere and the Sea in Motion, Rockefeller Institute Press and Oxford University Press, pp. 65-73.

-----, 1960: "Ocean Temperature and Atmospheric Circulation," WMO Bulletin, Vol. IX, No. 3, p. 151.

-----, 1964: "Atlantic Air-Sea Interaction," Advances in Geophysics, Vol. 10, Academic Press, New York.

-----, 1966: "A Possible Response of the Hadley Circulation to Variations of the Heat Supply from the Equatorial Pacific," Tellus, Vol. XVII, pp. 820-829.

-----, 1968: Atmospheric Teleconnections from the Equatorial Pacific, P-3882, The RAND Corporation, Santa Monica, California.

Borisov, P.M., 1959: "The Bering Strait Dam," Literaturnaya Gazeta, Moscow.

-----, 1967: "Can We Control the Climate of the Arctic?" Priroda, Issue 12, pp. 63-73.

Bristor, C.L., 1968: "Computer Processing of Satellite Cloud Pictures," ESSA Technical Memo NESCTM-3.

-----, 1967: "Satellite Data Collection," Proc. IBM Symposium, Western Research Center, Yorktown, New York.

Bryson, R.A., 1968: "All Other Factors Being Constant," Weatherwise, Vol. 21, No. 2.

Budyko, M.I., 1962: "Certain Means of Climate Modification," Meteorologiia i Gidrologiia, No. 2:3-8.

-----, O.A. Drozdov, and M.I. Yudin, 1966: "Influence of Economic Activity on Climate," Contemporary Problems of Climatology, Leningrad.

-----, 1967a: "Effect of Volcanic Eruptions on Solar Radiation Coming to the Surface of the Earth," Met. i Gid., No. 10.

-----, 1967b: "Variations of Climate," Met. i Gid., No. 11.

Callendar, G.S., 1938: "The Artificial Production of Carbon Dioxide and its Influence Upon Surface Temperature," Meteorol. Mag., Vol. 73.

-----, 1961: "Temperature Fluctuations and Trends over the Earth," J. Roy. Meteorol. Soc., Vol. 87, No. 371.

Davitaya, F.F., 1965: "The Possible Influence of Atmospheric Dustiness on the Recession of Glaciers and Warming of the Climate," Izv. Akad. Nauk SSSR, No. 2.

Fairbridge, R.W. (ed.), 1961: "Solar Variations, Climatic Change, and Related Geophysical Problems," Annals N.Y. Acad. Sci., Vol. 95, pp. 1-740.

Fletcher, J.O., 1965: The Heat Budget of the Arctic Basin and Its Relation to Climate, R-444-PR, The RAND Corporation, Santa Monica, California.

-----, (ed.), 1966: Proceedings of the Symposium on the Arctic Heat Budget and Atmospheric Circulation, RM-5233-NSF, The RAND Corporation, Santa Monica, California.

-----, 1968: The Interaction of Variable Sea Ice Extent with Global Climate, RM-5793-NSF, The RAND Corporation, Santa Monica, California. (forthcoming).

Gavrilin, B.L., 1965: "Numerical Experiments on the General Circulation of the Atmosphere," Izv. Atmos. Ocean Phys., Vol. 1, No. 12.

JPRS, 24512, "Review of Research and Development in Cloud Physics and Weather Modification," Soviet-Bloc Research in Geophysics, Astronomy, and Space, No. 83.

Kraus, E.B., 1954: "Secular Changes in the Rainfall Regime of East Australia," Quart. J. Roy. Meteorol. Soc., Vol. 80, pp. 591-601.

-----, 1955a: "Secular Changes in Tropical Rainfall Regimes," Quart J. Roy. Meteorol. Soc., Vol. 81, pp. 198-210.

-----, 1955b: "Secular Changes of East Coast Rainfall Regimes," Quart. J. Roy. Meteorol. Soc., Vol. 81, pp. 430-439.

-----, 1956: "Secular Changes of the Standing Circulation," Quart. J. Roy. Meteorol. Soc., Vol. 82, pp. 289-300.

-----, 1959: "The Evaporation-Precipitation Cycle of the Trades," Tellus, Vol. 11, pp. 147-158.

-----, 1963: "Recent Changes of East Coast Rainfall Regimes," Quart. J. Roy. Meteorol. Soc., Vol. 89, pp. 145-146.

Lamb, H.H., 1966a: The Changing Climate, London, Methuen.

-----, and A.I. Johnson, 1966b: "Secular Variations of the Atmospheric Circulation Since 1750," Geophysical Memoir No. 110.

-----, 1966c: "On Climatic Variations Affecting the Far South," 1966 WMO Technical Note No. 87, Geneva.

-----, 1966d: "Climate in the 1960's," Geophys. J., Vol. 132, Part 2.

Landsberg, H.E., 1963: "Unusual Weather of January 1963," Monthly Weather Review, Vol. 91, No. 6, pp. 307-308.

Maximov, I.V., 1954: "Secular Fluctuations of Ice Conditions in the Northern Part of the Atlantic Ocean," Trudy Inst. Oceanology, Vol. VIII, Moscow.

Mitchell, J.M., Jr., 1963: "On the Worldwide Pattern of Secular Temperature Change," Changes in Climate, Proc. Rome Symposium, UNESCO.

Möller, F., 1963: "On the Influence of Changes in the CO_2 Concentration in Air on the Radiation Balance of the Earth's Surface and on the Climate," J. Geophys. Res., Vol. 68, No. 13.

Namias, J., 1966a: "Large-Scale Air-Sea Interactions as Primary Causes of Fluctuations in Prevailing Weather," Trans. N.Y. Acad. Sci., Vol. 29, pp. 183-191.

-----, 1968: "Long-Range Weather Forecasting -- History, Current Status, and Outlook," Bull. AMS, Vol. 49, No. 5.

National Academy of Sciences, 1966: "Weather and Climate Modification," (2 vols.), Publ. No. 1350, Washington, D.C.

National Science Foundation, 1965: "Weather and Climate Modification," Publ. NSF 66-3.

Plass, G.N, 1959: "Carbon Dioxide and Climate," Scientific American No. 1.

Rubinstein, E.S., and L.G. Polozova, 1966: "Contemporary Climatic Variations," Hydrometeorological Publishing House, Leningrad.

Rusin, N.P., and L.A. Flit, 1962: Methods of Climate Control, Moscow.

Sandstrom, J.W., 1932: "Uber den Einfloss des Golfstromes auf das Wether," Physic der frelin Atmosphere, Leipzig.

Sawyer, J.S., 1966: "Possible Variations of the General Circulation of the Atmosphere," World Climate from 8000 BC to 0 BC, Proc. Symposium Royal Meteorological Society.

Shishkov, V.A., 1962: "Meridional Transfer of Heat in the Lower Troposphere and Anomalies of the Temperature Regime in the Northern Part of the Atlantic Ocean," Trudy Institute of Oceanologii ANSSSR, Vol. 57.

Sorkina, A.I., 1965a: "Comparison of the Regimes of Atmospheric Circulation over the North Atlantic and the North Pacific," Oceanology, Vol. 5, No. 3.

-----, 1965b: "Features of Atmospheric Circulation over the North Atlantic During the IGY and IGC," Oceanology, Vol. 5, No. 4.

Thompson, P.D., and W.O. Roberts, 1967: "Computing the Weather," Christian Science Monitor, August.

Vowinckel, E., and S. Orvig, 1964: "Radiation Balance of the Troposphere and of the Earth-Atmosphere System in the Arctic," Publications in Meteorology, No. 63, McGill University, Montreal.

Wexler, H., 1958: "Modifying Weather on a Large Scale," Science, Vol. 128, pp. 1059-1063.

Willett, H.C., 1953: "Atmospheric and Oceanic Circulation as Factors in Glacial-Interglacial Changes of Climate," Climatic Change, Harvard.

-----, 1965: "Solar Climatic Relationships in the Light of Standardized Climatic Data," J. Atmos. Sci., Vol. 22, pp. 120-136.

-----, 1961: "Solar Climatic Relationships," Annals N.Y. Acad. Sci., Vol. 95, Article 1, pp. 89-106.

Wyrtki, K., 1966: "Seasonal Variation of Heat Exchange and Surface Temperature in the North Pacific Ocean," Report 66-3, Hawaii Institute of Geophysics, Honolulu, 8 pp.

Yudin, M.I., 1966: "The Possibilities for Influencing Large-Scale Atmospheric Processes," Contemporary Problems in Climatology, Leningrad.

Zikeev, N.T., and G.A. Doumani, 1967: Weather Modification in the Soviet Union 1946-1966, A Selected Annotated Bibliography, Library of Congress, Washington, D.C.