MANAGING CLIMATIC RESOURCES

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INTRODUCTION

Recent years have seen an upsurge of research in the fields of weather modification and climate control. Substantial improvements in the accumulation and analysis of environmental data, coupled with a better understanding of the nature and interrelationship of climatic processes, have provided researchers with theoretical insights into how global climate can be modified and what some of the resulting consequences might be. Man already has the technological capability to carry out many climate-influencing schemes, such as the creation of large inland seas, the deflection of ocean currents, the seeding of extensive cloud or surface areas, and perhaps even the removal of the Arctic pack ice. Still unresolved, however, is the uncertainty about the possible global effects of such large-scale weather modification efforts, which, in addition to bringing about major environmental changes, would give rise to many complex economic, sociological, legal, and political problems.

As internationally-pursued research efforts continue to improve our knowledge of climatic processes and the possibilities of deliberately influencing them, we are also becoming increasingly aware of the disturbing fact that human activity may already be inadvertently and irreversibly influencing global climate. Furthermore, the inadvertent consequences of human activity will increase manyfold in only a few decades, precisely at a time when rapidly growing pressures on world food

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production make the social consequences of climatic variation ever more serious. The inescapable conclusion is that purposeful management of global climatic resources will eventually become necessary to prevent undesirable changes. That such capabilities could be used to improve existing climatic conditions is obvious.

Let us, therefore, consider the nature of the physical problem, the depth of our present understanding of it, the feasible influencing capabilities available to us, and the prospects for future progress.

THE INADVERTENT INFLUENCING OF GLOBAL CLIMATE

Whether human activity has played a significant role in 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 to assess the dynamical response of the system to a given change. Some 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, particulate pollution (smog and dust), 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 (the other two being water vapor and ozone). There is no doubt that the carbon dioxide concentration in the atmosphere has been increasing in this century, apparently by some 10-15%, due primarily to the increased combustion of carboniferous fuels. The physical effect of a greater CO_2 concentration in the atmosphere is to decrease the radiative loss to space. Thus, an increase in CO_2 causes global warming. Some have suggested that the warming since 1900 was due to just such an increase in the atmospheric content of CO_2. Plass (1959) estimates that a warming of $.5^{o}C$ during the last century could be attributed to this cause, and this is comparable to the warming that did occur. It is further estimated that, by the year 2000, a further warming of three times this amount could be caused by the increase of CO_2 in the atmosphere. Other estimates have predicted an even greater warming. Notwithstanding these arguments, the sharp global cooling of the past decade indicates that other, oppositely-directed factors are more influential than the increasing atmospheric content of CO_2. For example, Moller (1953) estimates that a 10% change in CO_2 can be compensated for by a 3% change in water vapor or by a 1% change in mean cloudiness. Moreover, the oceans have an enormous capacity to absorb CO_2, this varying according to their temperature, with colder oceans being able to store more CO_2. Thus, a warming of the oceans could also be a primary cause of the increase of CO_2 in the atmosphere. In summary, it appears that, other factors being constant, the CO_2 generated by human activity could bring about important changes of global climate during the next few decades. But other factors, of course, are not constant, and have apparently been more influential than the CO_2 increase in affecting the climate of recent years.

With regard to heat pollution, Budyko (1962, 1966) points out that, although the yearly production of man-made energy on Earth is now only about 1/2500 of the radiation balance of the Earth's surface, it could increase to equal the surface radiation balance if compounded annually at 10% for 100 years, or 4% for 200 years. (The present growth rate is about 4% and causes a doubling every 17 years.) From these numbers we may conclude that, sometime during the next century, the problem of heat pollution will become important on a global scale. By then we must be able to compensate for it or face the possibility of a sharp global warming which could, in turn, trigger additional reinforcing transformations such as a melting of the polar ice. But, for the time being, and for the next few decades, the effects of heat pollution will not be sizable enough to exert a significant influence on global climate.

Budyko (1966) also considers the environmental effects of forest belts, irrigation projects, swamp drainage, and large, artifically-created reservoirs. Such projects can greatly influence the climate of a local region, but none seem likely to significantly affect global processes.

One of the most rapidly increasing forms of man-made atmospheric pollution is smog, which embodies all forms of industrial pollution. We can frequently observe bodies of water becoming increasingly more polluted by excretions of industrial sewage. What we can not observe as easily is that the ocean of air in which we live is also becoming ever more polluted and turbid. Bryson (1968) reports a turbidity increase of 30% per decade over Mauna Loa Observatory, which is far from all sources of pollution and is thus indicative of the general increase. He further argues that a more turbid atmospheric transparency, even by only 3-4%, could decrease the global mean temperature by .4°C. This is due to the fact that a more turbid atmosphere will reflect back more of the Sun's radiation, thus allowing less heat to penetrate through to the Earth. Bryson believes that the increasing global air pollution, through its effect on the reflectivity of the Earth's atmosphere, is currently the dominant influence on climate and is responsible for the temperature decline of recent decades. Budyko (1968) also attributes climatic changes primarily to the decreased transparency of the atmosphere, caused in the past by volcanic eruptions and in recent decades by man-made pollution. If this interpretation is correct, mankind faces an immediate and urgent need for global climate management, especially in view of the fact that smog production is increasing everywhere at an exponential rate and no means of curbing this increase are in sight.

Curve 6 in Fig. 1 shows the observed trends of atmosphere transparency since 1890 and a general correspondence with some of the other variations in the global system can be seen. The sharp decrease in transparency early in this century can be attributed to a series of volcanic eruptions. However, the decrease since 1940 cannot be attributed to this cause, although the eruption of Agung in 1963 did cause a noticeable world-wide effect. Thus, man-made pollution may have been the most important cause of recent climatic changes.

On the other hand, there also appears to be a connection between solar activity and atmospheric transparency. Curve 5 in Fig. 1 shows the trends of sunspot activity and one can see that much of the recent decrease in atmospheric transparency might be accounted for on this basis. If this is true, a reversal should become apparent during the next decade, when fewer sunspots are expected.

Still another form of growing pollution, and one whose possible effects have received little study, is the creation of cirrus cloudiness (vapor trails) by the exhaust products of high-flying aircraft.

Increased cloudiness of any form tends to increase the reflectivity (albedo) of the Earth and, according to Bryson's calculations, a 1% increase in mean albedo would cool the Earth by 1.6°C. However, it should be noted that increased cloudiness at high levels greatly reduces radiative loss to space, and this would have a warming effect on the Earth. Thus, the dual effects of more or less cloudiness are great, but the direction of the net influence depends on the type and height of the clouds, and on whether they are in a dark or sunlit region of the Earth.

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 still very uncertain. In order to better understand this uncertainty, let us take a brief look at the dynamic and multifaceted nature of global climate.

THE CHANGING PATTERN OF GLOBAL CLIMATE

The climate of a particular region is determined by a number of relatively static factors such as elevation, latitude, topography, type of surface, and also by the properties of the air which passes over it. The dynamic factor which brings about weather changes is the circulation of the atmosphere, which, in turn, is strongly influenced by the interaction of the ocean/atmosphere system. Variations in the mean behavior of the atmospheric circulation over a period of years constitute variations of climate.

Substantial worldwide changes of climate have occurred, even in the course of a few decades, and have been described by many investigators (Mitchell, 1963; Willett, 1965; Lamb, 1966; Rubinstein and Polozova, 1966). The data shows that the general vigor of the global atmospheric circulation undergoes significant variations, with associated latitudinal shifts of the main wind currents and changes in the nature of their disturbances. Variation in the global atmospheric circulation pattern is the 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 general trend was toward a growing strength of the Northern Hemisphere circulation, a northward displacement of polar fronts (outer boundaries of cold masses) in both the atmosphere and the ocean, a northward displacement of pack ice boundaries and cyclone paths (movements of large, rotating wind currents), a weaker development of blocking air masses over the continents, and a pronounced aridity of the south central parts of North America and Eurasia. Conversely, recent decades have exhibited opposite trends: a weakening circumpolar circulation, southward shifts of ice boundaries and cyclone paths, and increased rainfall in the south central parts of the continents.

These trends were underscored in 1968. It was a year in which Icelandic fishermen suffered losses due to the most extensive sea ice in the last half century, while phenomenal wheat yields from the plains of both Asia and North America pushed world wheat prices to a 26-year low. The predicted 1968 famine in India did not occur, with favorable climate and better strains of grain as the important offsetting factors. In the Southern Hemisphere, the southward displacement of the Chilean rainfall region created severe droughts.

Such small variations of climate, though of growing importance to our complex pattern of human activity, are minor compared to the more pronounced variations that have occurred in the relatively recent past. Less than 20,000 years ago, an ice sheet still covered North America and stretched from the Atlantic to the Pacific with a thickness of up to two miles. The last major ice sheet disappeared from Scandinavia only about 8000-7000 BC, while in North America the ice retreated even later. During the period of ice retreat and somewhat after, rainfall in the Mediterranean area and probably over much of the hemisphere was less than at present, possibly due to cooler oceans. The post-glacial warming culminated in a "climatic optimum" about 4000-2000 BC, during which world temperatures were 2-3°C warmer than they are now, and rain was much more plentiful in North Africa and the Middle East.

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, which was accompanied by the rapid development of human activity partly induced by climatic stress. By this time, renewed warming had set in and continued until a "secondary climatic optimum" of 800-1000 AD, a period characterized by a relatively rainless, warm and storm-free North Atlantic, which made possible the great Viking colonization of Iceland, Greenland and Newfoundland. The subsequent climatic decline, during which Arctic pack ice advanced southward in the North Atlantic, was abrupt from about 1300 AD, with one partial recovery around 1500, and culminated in the "little ice age" of 1650-1840.

Since about 1840, a new warming trend predominated and appears to have reached a climax in this century, followed by cooling since about 1940, irregularly at first but more sharply since about 1960. The periods of general warming were accompanied by increasing vigor of the westerly circulation in both hemispheres, bringing a more maritime climate to the continents, a northward displacement of cyclone paths, and a pronounced warming of the Arctic. The recent cooling trend exhibits a reverse pattern: weakened westerly circulation, more variable and southerly cyclone paths, and a colder Arctic.

The pattern of change in the Southern Hemisphere is more obscure. No reliable index has been found for the strength of the Southern Hemisphere trade winds and even the indices of mid-latitude westerlies are not adequate. Temperature patterns for the 80 percent of the Southern Hemisphere covered by oceans are almost nonexistent. Even since the IGY, year to year variations in sea ice extent in the Southern Ocean are largely unknown. However, the meager data that are available show that corresponding climatic variations are evident from pole to pole. This is illustrated by Fig. 1 which shows similar trends for the mean surface temperature in the Northern Hemisphere, the snow accumulation at the South Pole, and the iciness of the Weddell Sea, all representing manifestations of variations in the global system.

THE GLOBAL "CLIMATE MACHINE"

It is increasingly apparent that climatic change can be explained only in terms of the behavior of the atmosphere and ocean on a global scale. Net heating at low latitudes and net cooling in polar regions forces the motion of the atmosphere, which, in turn, drives the surface circulation of the ocean (Fig. 2). On the average, the atmosphere and oceans transport heat vigorously enough to balance the difference in heat loss between equator and poles, with atmospheric motion transforming potential energy into kinetic energy at a rate which balances frictional dissipation. Climatic variations seem to be associated with variations in the vigor of the whole global 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. Fundamental physical laws should then enable us to predict the global distribution of temperature, pressure, motion, water vapor, clouds, and precipitation, together with resulting moisture and heat transports. In practice, this presents enormous difficulties. However, with the development of modern computer technology, rapid progress is being made. Already it is becoming possible to mathematically simulate certain large-scale processes in more detail than we now observe them in nature.

This progress toward simulating atmospheric dynamics calls for a better understanding of the processes of atmospheric heat losses and gains which force the motion of the real atmosphere. Variations in equatorial heating and polar cooling are poorly understood and have received little study, largely because of the paucity of relevant data.

Nevertheless, it has been discovered that significant year to year variations in ocean/atmosphere heat and moisture exchange do occur and that these anomalies are closely related to observed variations in the dynamical behavior of the atmosphere. Thus, for instance, variable cloudiness influences the fraction of solar radiation reflected back to space, evaporation and sensible heat from ocean to atmosphere depends on wind speed, and persistent anomalies of surface winds change patterns of ocean circulation and upwelling.

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. This zone is created by the opposite deflection of warm 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, a 1963-64 expedition found a cold equatorial tongue nearly 10^{o} colder than surrounding waters ($28^{o}C/18^{o}C$) (Lamb, 1966d).

During some years, these cold tongues weaken or vanish as the equatorial trade winds wane. Bjerknes (1966) has documented several such cases for the Pacific, showing that the resulting variation of evaporation and subsequent condensation influences the atmospheric 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 such processes are associated with the rise of East African rainfall since 1961-63. Indeed, the frequency of such occurrences may be closely connected with the changes in the global system since 1961-63 (Lamb, 1966d).

The interaction of large-scale atmospheric and oceanic circulation in the Indian Ocean is known to vary from year to year. Understanding this interaction is not only necessary for understanding global climate, but has immediate application for forecasting the southwest monsoon, which directly affects the crops and economy of one of the most densely populated areas in the world.

Our present state of knowledge cannot yet explain 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 westerlies, and the longitudinal shifts of mean troughs and ridges. There is growing evidence that variations of the Northern Hemisphere circulation may be influenced by variations of the much stronger Southern Hemisphere circulation, but the basic cause of the planetary variation is still obscure.

Impressive statistical correlations between various indices of climatic change and various indices of solar activity have been presented by many investigators (Fairbridge, 1961; Rubinshtein and Polozova, 1966), but no one has yet been able to advance a physically-plausible cause and effect explanation. Curve 5 in Fig. 1 shows the similarity of solar variations and global climatic variations. Variations in the solar "constant" are usually judged to be too small to account for the relatively-large observed variations of global climate. Therefore, 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 at the surface 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, 1969).

VARIABLE ICE EXTENT ON THE OCEAN AS A CLIMATE "TRIGGER"

The presence of sea ice effectively prevents the transfer of heat from ocean to atmosphere in winter, thus forcing the atmosphere to balance the radiative heat lost to space. For example, in January the mean surface temperature in the central Arctic is about -30°C, while a few feet below the pack ice, the ocean water is near -2°C. The ice and its snow cover are such a good insulator that relatively little heat reaches the surface from below. The surface radiates heat to space, and this heat loss simply cools the surface until it is cold enough to drain the needed heat from the atmosphere. The thermal participation of the ocean is greatly suppressed. If the ice were not there, the needed heat would be obtained from the relatively warm ocean.

In summer, on the other hand, an open ocean would absorb around 90 percent of the solar radiation reaching the surface, instead of the 30-40 percent presently absorbed by the year-round pack ice. Thus, the presence of the ice suppresses heat loss by the ocean in winter and suppresses heat gain by the ocean in summer. For the atmosphere, of course, the reciprocal relation applies; over pack ice, the atmosphere cools more intensely during winter and warms more intensely in summer. In this way, variable ice extent can amplify the effect of small variations in solar heating. Thus, a decrease in solar radiation causes cooling, which causes ice extension, which in turn cools the atmosphere more, causing further ice growth and stronger thermal gradients. The causes and effects are self-reinforcing, and provide "positive feedback." How far such a process must go before it triggers 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 thickness of the pack ice, had continued? As the ice would recede farther in summer and the thinner ice would become more fractured in winter, evaporation would increase, thus salifying 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, namely, the initial condition. Thus, a "threshold" exists in each direction -- destruction of stratification which prevents refreezing and the eventual depletion of heat content which triggers refreezing.

Budyko (see Fletcher, 1966) has argued that, under present conditions of solar heating, the Arctic pack ice would not reform if it were removed. Instead, a new and stable climatic regime would be established in which the Arctic Ocean would remain ice-free.

To answer such questions with more certainty we really need to model the entire planetary circulation under the assumption of an ice-free Arctic Ocean, but as yet this has not been adequately done. However, detailed calculations of zonal temperature distribution at various levels under conditions of an ice-free Arctic have been made by Rakipova (see Fletcher, 1966) using a theoretical model of zonal temperature distribution. According to these calculations, the intensity of atmospheric circulation would decrease, but much more so in the winter than in the summer, so that seasonal contrasts would be much smaller than at present. In high latitudes, poleward atmospheric heat transport would decrease by about 25 percent during the cold half year, and the Arctic Ocean would remain ice-free. In summary, it appears that a sufficient warming of global climate would lead to the disappearance of the Arctic pack ice, at which time a new and relatively stable climatic regime would be established. Such a regime, while bringing a more temperate climate to the subpolar areas, could make other parts of the world considerably more arid.

Budyko (1968) used a similar empirical approach to estimate the influence on global climate, during planetary cooling, of the interaction of variable solar radiation, changing ice extent, and mean global surface temperatures. For his highly idealized model he concludes that, in the event mean solar radiation over the earth decreases by 1%, the mean global temperature would drop by 5°C, the cooling being reinforced by an advance of the ice boundary by about 10° of latitude in both hemispheres. Should the solar radiation decrease by 1.5%, the global temperature drop would be 9°C, and the ice advance would be 18° of latitude. If the radiation decrease were more than 1.6%, the ice boundary would advance past the 50° latitudes in both hemispheres, and the cooling due to the large ice area would cause continued ice growth until all the oceans were frozen. Once such a condition was established, melting would not occur even with a substantially higher solar radiation intensity.

It should be noted that the empirical dependencies used by Budyko were calculated from Northern Hemisphere climatic data and he assumes that the Southern Hemisphere would respond similarly. This assumption probably exaggerates the sensitivity of global climate to solar variations, but Budyko's dramatic conclusions illustrate the necessity of taking such feedback processes into account. Ice extent is probably the most influential factor capable of quickly transforming the large scale thermal properties of the earth's surface. Thus, understanding the interaction of ice extent, radiation variations and atmospheric circulation is fundamental to understanding global climatic changes.

POSSIBILITIES FOR PURPOSEFUL INFLUENCE ON GLOBAL CLIMATE

Theoretical perspectives for modifying global climate by influencing large-scale atmospheric circulation have been discussed by Yudin (1966), who emphasizes that since the energies in nature are so vast compared to man's capabilities, ways must be found to trigger natural instabilities in ways that use relatively small energy inputs. For example, it would be desirable to be able to act directly on the field of motion, avoiding intermediate links in the natural cycle which involve conversion of heat into potential energy and then to kinetic energy. Yudin points out that, in theory, it should be possible to influence the velocity field with much less energy than is needed to change the temperature field or pressure field. Moreover, in influencing the velocity field, energy should be applied evenly over a broad area to minimize the dissipation of energy by parasitic acoustical and gravity waves. Yudin further points out that particular components of the velocity field are especially subject to influence.

Yudin then proposes that, following these precepts for the application of energy, emphasis should be placed on identifying critical "instability points" in the natural development of cyclones. For example, only slight deflections of certain winds are associated with a faster movement of cyclone centers.

These brief criteria clearly identify one difficulty associated with large-scale weather modification, namely that the theoretically most effective approaches involve actions that we do not know how to produce efficiently. On the other hand, various ways of influencing the heat losses and inputs to the atmosphere, although theoretically inefficient from the viewpoint of immediate dynamical consequences, are much more achievable with present technology. It has, for example, 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 of cloud surface. It is estimated that it would take only sixty C-5 aircraft to deliver 1 kg per km^2 per day over the entire Arctic Basin (10^7km^2). Thus, it is a large but not an impossible task to seed such enormous areas.

Assuming that such seeding were effective in creating or dissipating clouds, it is of interest to estimate the effect of such cloud modification on the heat budget of the surface/atmosphere system. It is estimated that the presence of average cloudiness over the Arctic in July decreases the radiative heat loss to space by about 350 billion cal/km^2/day from what it would be without clouds. By comparison, total cloud at 500 meters would decrease radiative loss by only 50 billion cal/km^2/day, while total cloud at 5000 meters would decrease radiative loss by about 1000 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 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 heat loss at the surface have been observed to vary by more than 100% in different years at some Arctic stations, possibly due to variations in cloudiness.

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

Influencing the temperature of extensive ocean surface areas by changing the courses of certain ocean currents has also been proposed (Rusin and Flit, 1962). These schemes involve large, but not impossible, engineering efforts, some of which are discussed in the next section. The principal difficulty, however, is that the 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 until more realistic simulation models have been developed.

These various examples demonstrate the following essential conclusions:

(1) It does appear to be within man's engineering capacity to influence the loss and gain of heat in the atmosphere on a scale that can influence patterns of thermal forcing of atmospheric circulation.

(2) Purposeful use of this capability is not yet 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 inadvertent influences of man's activity may eventually lead to catastrophic influences on global climate unless ways can be developed to compensate for 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.

SPECIFIC SCHEMES FOR CLIMATE MODIFICATION

Many engineering proposals have been advanced for improving the climatic resources of particular regions. All of these schemes share the common defect that their influence on the global system cannot yet be reliably judged. Some are on a scale that could well influence the global system and possibly even trigger instabilities with far reaching consequences. Sooner or later, some such schemes may be carried out, and it is of interest to consider them in the larger perspective discussed here (Rusin and Flit, 1962).

Ice-Free Arctic Ocean

The largest scale enterprise that has been discussed is that of transforming the Arctic into an ice-free ocean. As was noted earlier, this has been very carefully studied by the staff of the Main Geophysical Observatory in Leningrad. The central question is the stability of the ensuing global climatic regime. This question cannot be adequately evaluated until global climate simulation models are better developed and suitable simulations performed.

There is also a certain amount of uncertainty in regard to the engineering feasibility of removing the Arctic pack ice. It is possible that the capacity of present technology may be sufficient to accomplish this task, but this has not been established. Three basic approaches have been proposed (Fletcher, 1965): (1) influencing the surface reflectivity of the ice to cause more absorption of solar heat; (2) large-scale modification of Arctic cloud conditions by seeding; (3) increasing the inflow of warm Atlantic water into the Arctic Ocean.

Bering Strait Dam

Soviet engineer Borisov (1959, 1967) has been the most active proponent of the much-publicized Bering Strait Dam. The basic idea is to increase the inflow of warm Atlantic water by stopping or even reversing the present northward flow of colder Pacific water through the Bering Strait. The proposed dam would be 50 miles long and 150 feet high. The net climatic effect of the project, if it were carried out, is still highly uncertain. A good argument can be made that the effect would be less than the variation in the Atlantic influx that occurred naturally in connection with the climatic changes depicted by Fig. 1.

Deflecting the Gulf Stream

Two kinds of proposals have been discussed -- a dam between Florida and Cuba, and weirs extending out from Newfoundland across the Grand Banks to deflect the Labrador current as well as the Gulf Stream. None of these proposals have been supported by detailed engineering studies or reliable estimates of what the resultant effects would be.

Deflecting the Kuroshio Current

The Pacific Ocean counterpart of the Gulf Stream is the warm Kuroshio Current, a small branch of which enters the Sea of Japan and exits to the Pacific between the Japanese islands. It has been proposed that the narrow mouth of Tatarsk Strait, where a flood tide alternates with an ebb tide, be regulated by a giant one-way "water valve" to increase the warm inflow to the Sea of Okhotsk and reduce the winter ice there.

Creation of a Siberian Sea

Dams on the Ob, Yenisei and Angara Rivers could create a lake east of the Urals that would be almost as large as the Caspian Sea. This lake could be drained southward to the Aral and Caspian Seas, irrigating a region about twice the area of the Caspian Sea. In terms of climatic effects, the presence of a large lake transforms the heat exchange between the surface and atmosphere. And, of equal or greater importance is the land region transformed from desert to growing fields, with accompanying changes in both its reflectivity and evaporation.

Creation of African Seas

This is the largest known proposal for creating man-made lakes. If the Congo, which carries some 1200 km^3 of water per year, were dammed at Stanley Canyon (about 1 mile wide), it would impound an enormous lake (the Congo Sea). The Ubangi, a tributary of the Congo, could then flow to the northwest, joining the Chari and flowing into Lake Chad, which would grow to enormous size (over 1,000,000 km^2). This large lake (the Chad Sea) would approximately equal the combined areas of the Baltic Sea, White Sea, Black Sea, and Caspian Sea. The two lakes would cover 10% of the African continent. They could then be drained north across the Sahara, creating an extensive irrigated region, similar to the Nile Valley.

NAWAPA Project

The proposed North American Water and Power Alliance is a smaller scale scheme. It would bring 10^8 acre feet of water from Alaska and Canada to be evaporated by irrigation in the western United States and Mexico. The possible climatic effects are highly speculative. For example, would the increased moisture in the air fall out again over the central U.S., or would it be transported to some other region?

PROSPECTS FOR FUTURE PROGRESS

It is convenient to think of progress toward climate control 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.

From the foregoing examples it is evident that modern technology is already capable of influencing the global system by altering patterns of thermal forcing, but the consequences of such acts cannot be adequately predicted. The global system is a single, interacting "heat engine" in which a substantial action anywhere may influence subsequent behavior everywhere. At present, we do not understand the system well enough to predict this behavior. Much progress in observation, understanding, and prediction is needed before purposeful climate modification can become feasible, but a more rapid progress can now be anticipated.

Progress in understanding climatic change has been slow and uneven. Observed changes in climate in the 1890's stimulated much speculative interest and triggered a flood of theories based on qualitative arguments. But, with no way to test theories about the behavior of such a complex system, very little real progress in understanding resulted. Even today, an adequate theoretical basis has not been developed for explaining the interactions of the global heat engine and accounting for observed changes in climate. Causal relationships are obscured by the multitude of factors involved, and problems for investigation are often ill-defined. Research methods are often painfully slow and frustrating, and thus less attractive to young scientists than the more direct methods of the experimental sciences involving: observation of physical behavior, formation of a hypothesis, deduction of consequences from the hypothesis, and the testing of deductions by physical experiment. Until now, there has been no way to experimentally test a theory of climatic change.

In theory, it should be possible to solve the equations which describe the behavior of the atmosphere and the ocean, given the conditions of thermal forcing and the initial state of the system. Such a quantitative analytical approach was formulated by V. Bjerknes in 1904 and expanded by Richardson in 1922. But, since neither the means to observe the state of the system nor the necessary computational power existed, such an approach had little immediate impact. Recent technological breakthroughs are removing these barriers and we are now entering a period of rapid progress.

As recently as World War II, not more than about 20% of the global atmosphere was observed at one time. With the advent of satellite observing systems, some quantities are now observed over the entire planet every day. This observational breakthrough makes possible the surveillance of the entire global system, and the sophistication of the observations that can be made by satellite is rapidly increasing.

Modern computer technology is rapidly overcoming the computational aspects of the problem. Mathematical simulation of the interacting ocean/atmosphere system has already been demonstrated. With computers now being developed that are 500 to 1000 times faster than existing models, we can reasonably hope that such simulation can be performed in enough detail to reliably evaluate the consequences of specific climate modification acts. With a straightforward means of testing hypotheses, we can expect a surge of new interest in theories of climatic change.

Such simulation capability also provides a means for making long-range forecasts, such as for a season or longer, based on observed and predicted conditions of thermal forcing. This will lead to a shift of emphasis in observing the global system. A short-range forecast can be based largely on the inertial behavior of the atmosphere, and the "machine forecasts" of the last decade have basically been of this type. The needed input data for such a forecast is a detailed description of the initial state, especially the field of motion. Patterns of thermal forcing are too slow-acting to be important in this short-range context. On the other hand, for a very long time period, we may expect that the mean behavior of the system will depend primarily on thermal forcing and be relatively independent of the initial dynamical state. It follows that the growing capability for climate simulation and long-range forecasting must also place new emphasis on observing and understanding the processes by which heat is exchanged between the ocean and the atmosphere. Today, we are not yet able to observe the global system in enough detail to know whether or not we are simulating realistic patterns of thermal forcing.

The presently-foreseeable ways by which global climate may be influenced all reduce to changing, in one way or another, the pattern of thermal forcing of atmospheric circulation. Such changes occur naturally for a variety of reasons. Understanding how and why they occur is the key to explaining observed changes of climate and also a necessary step toward being able to evaluate the consequences of man-induced changes.

Climatically-important variations in surface characteristics and surface heat exchanges occur naturally and to some extent may be influenced by man. In ocean areas, anomalies of surface temperature occur as a result of the wind-driven oceanic circulation. In land areas, the reflectivity and moisture capacity varies with the extent of vegetation. In ice areas, the reflectivity falls abruptly when melting begins. Of special importance is the variable extent of ice on the sea, for the presence or absence of ice determines whether the thermal characteristics of the surface will resemble those of land or those of ocean. The climatic significance of this factor can be appreciated by noting that about 12 percent of the world ocean is ice-covered at some time during the year, but only about 4 percent is ice-covered during the entire year. That is to say, the thermal behavior of some 8 percent of the world ocean area is ocean-like for part of the year and land-like for part of the year, a variable factor of possibly great climatic influence. Figure 3 shows available observational evidence of this relationship (Fletcher, 1968); variations in iciness of the Antarctic waters (lower curve) shows a high correlation with variations in the character of Northern Hemisphere atmospheric circulation about five years later. We might surmise that five years is comparable to the oceanic circulation time from the Southern Ocean to the equator, that variations in the Southern Ocean cause variations in the tropical ocean a few years later, and that these variations in ocean temperatures influence Northern Hemisphere circulation (Fig. 2), but without more complete observational data, or a realistic simulation model, such a hypothesis cannot be easily tested. Only in

1968 are ocean temperature patterns and the extent of ice on the sea beginning to be observed on a regular basis. A suitable ocean/atmosphere simulation model will probably be available within five years.

Finally, 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 more distant past. Defining the patterns of these changes is a way of observing nature's own "climate control experiments." The collection and systematization of paleoclimatic evidence is a task of great practical importance.

From the foregoing considerations one arrives at a conclusion of great significance, namely that we are reaching, or perhaps have already reached, a technological threshold from which progress can be proportional to the investment of effort. This conclusion, combined with the proposition that sooner or later purposeful climate modification is inevitable, deserves the attention of scientific and government leaders who must organize the needed resources.

INTERNATIONAL COOPERATION

The management of global climatic resources is a problem shared by all nations. So far, international efforts in climatic research have been directed toward observation and understanding, and cooperation has been good. It is a challenge to political and scientific leadership to preserve this spirit of cooperation as further progress is achieved toward prediction and control.

In 1961, President John F. Kennedy, in a statement to the United Nations, proposed "further cooperative efforts between all nations in weather prediction and eventually in weather control." In response, on 11 December 1961, the U.N. adopted a resolution [Resolution 1721] calling on all of its member states to join in a cooperative world weather program.

A first step was taken the following year, when the World Meteorological Organization [WMO] created a special working group to make a proposal in response to this resolution. In 1963, a program known as World Weather Watch -- the WWW-- took shape under the auspices of the WMO.

The goals of the WWW are immediate: to improve the accuracy of weather predictions and extend their usefulness to many new areas.

Most of the U.N. member nations, showing awareness of the great potential gains in human well-being promised by improved weather observations and predictions, have participated according to their ability and resources, and have already become actively involved in the World Weather Watch. On the part of the United States, a national policy was affirmed in 1968 as follows:

> RESOLVED BY THE SENATE OF THE UNITED STATES
> [The House of Representatives concurring]
>
> That it is the sense of Congress that the United States should participate in and give full support to the world weather program which included [1] a world weather watch -- the development and operation of an international system for the observation of the global atmosphere and the rapid and efficient communication, processing, and analysis of world-wide weather data, and [2] the conduct of a comprehensive program of research for the development of a capability in long-range weather prediction and for the theoretical study and evaluation of inadvertent climate modification and the feasibility of intentional climate modification....
>
> From the Congressional Record [Senate], 1 April 1968.

The ongoing observational programs emphasize certain typical regions, studying them in great detail and 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 regions, 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 progress achieved by cooperative international efforts will bring us closer to a realistic capability for managing global climatic resources. Let us hope that the spirit of international cooperation will continue to grow.

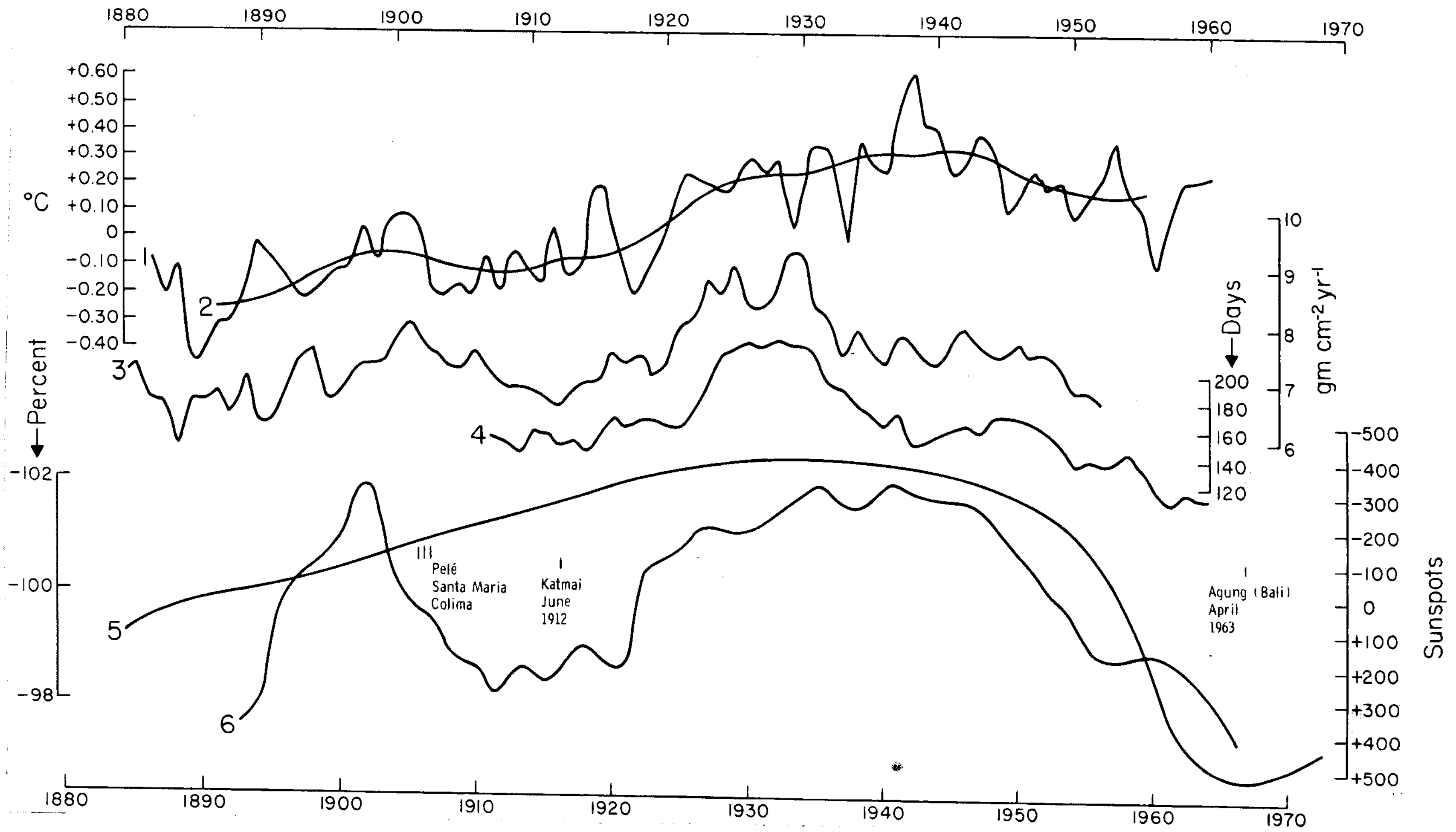
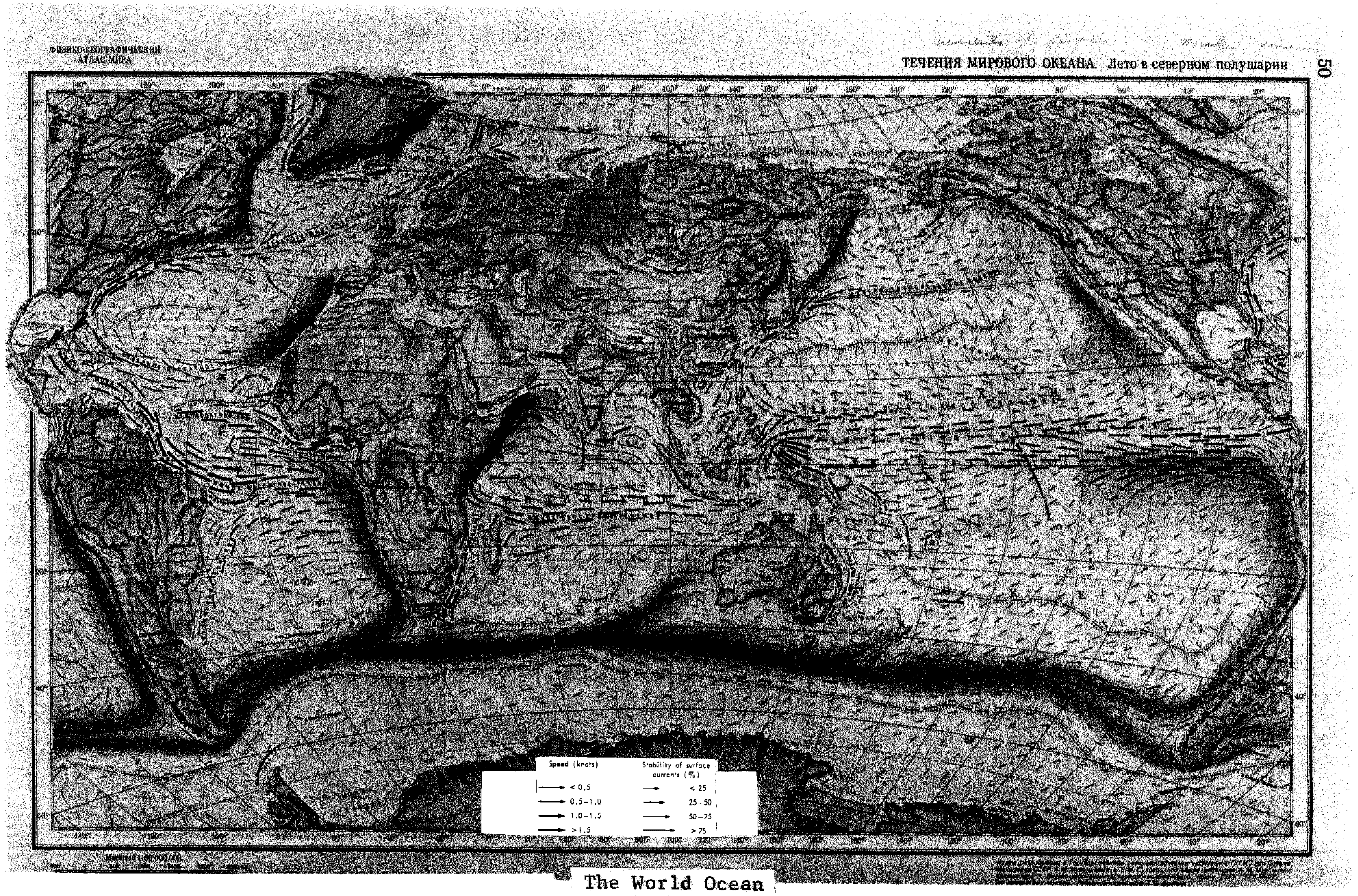


Fig. 1 -- Yearly indices of iciness of Antarctic and Arctic Seas, snow accumulation at the South Pole, Northern Hemisphere temperature. 1) Unsmoothed; 2) 10-year moving average. Deviation from mean annual temperature in the Northern Hemisphere, from monthly maps of anomalies 1881-1960 (Budyko, 1968); 3) 10-year moving average of annual snow accumulation at the South Pole (Giovinetto and Schwerdtfeger, 1966); 4) Iciness of the Weddell Sea, Antarctica. Number of days with ice on the bay at Orcadas, 10-year moving average (Schwerdtfeger, 1959); 5) Cumulative deviations from mean number of sunspots (Nazarov, 1963); 6) Variation of direct solar radiation with cloudless sky from stations in Europe and America (Budyko, 1968).



The World Ocean
(Southern Winter)

Fig. 2 -- Forced by strong westerly winds, the Southern Ocean is free to circulate in a circumpolar pattern, which -- owing to the absence of density stratification -- extends to the full depth of the ocean. Both the deep and surface waters of the Atlantic, Indian and Pacific Basins are influenced by interaction with the Southern Ocean.

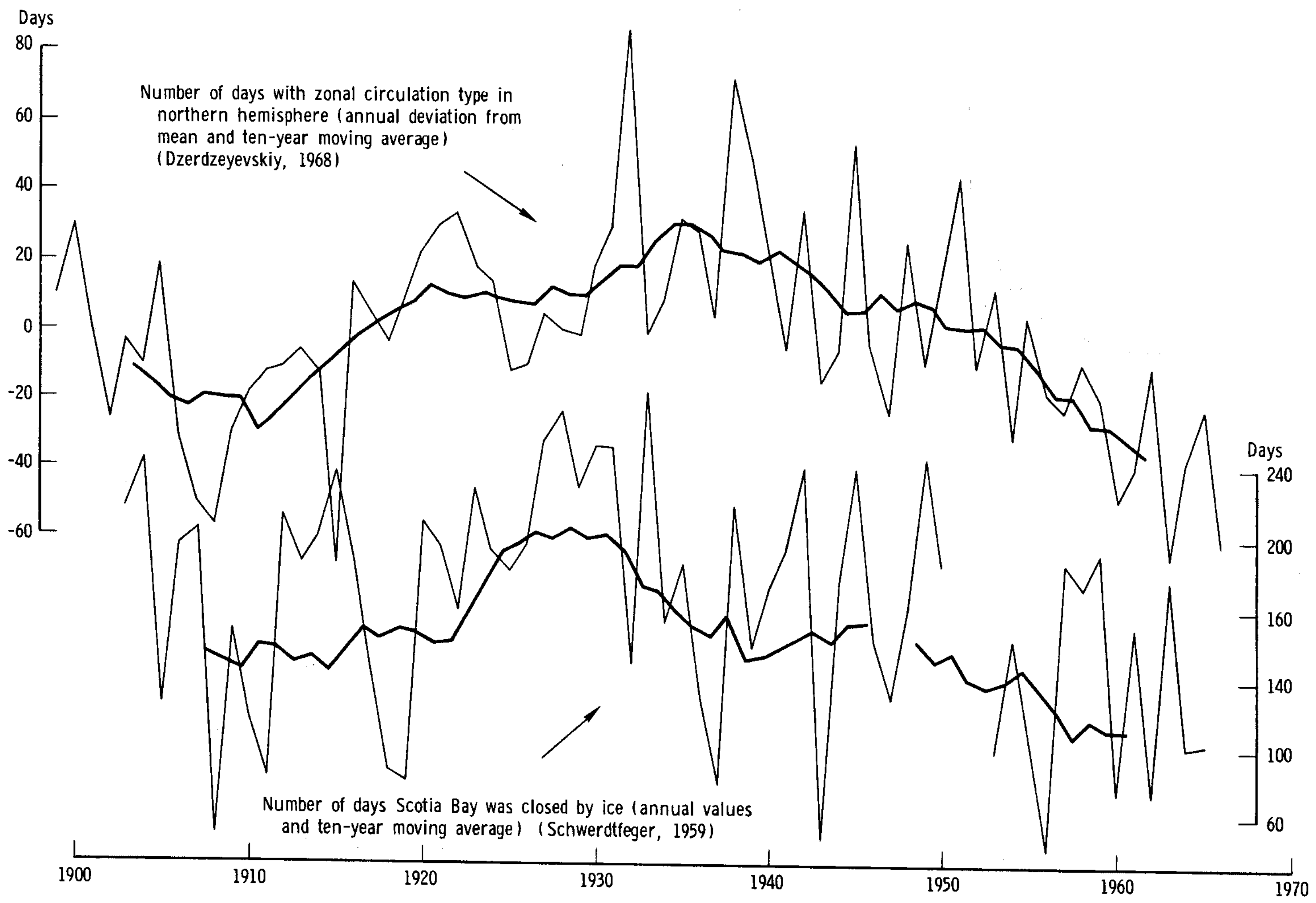


Fig. 3 -- Variations in the basic character of northern-hemisphere atmospheric circulation and in the iciness of the Weddell Sea.

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