A Theory of Ice Ages III

The theory involving polar wandering and an open polar sea is modified and given a quantitative basis.

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In our original theory of ice ages (*1*) we proposed that Quaternary glaciation is initiated by the migration of the geographic poles to regions of thermal isolation—that is, to the Arctic Ocean and Antarctica. Glacial-interglacial alternations were explained by the variability in the moisture supply for glacial growth, a variability resulting from the alternations of ice-covered with ice-free states of the Arctic Ocean.

Although we still adhere to the fundamentals of this twofold model, important modifications have been made on the basis of new material that has become available. The changes in the model which apply to the glacial-interglacial aspect are, in summary, as follows: (i) the freezing of the Arctic Ocean surface, initially postulated to have occurred at the termination of a glacial stage (about 11,000 years ago in the case of the Wisconsin, or Würm, stage) must have occurred considerably earlier; (ii) the moisture source for the growth of the southern half of the North American ice sheet must have been, not the Arctic Ocean, but the rich southerly source usually assumed for the growth of the entire ice sheet; (iii) the termination of a glacial stage is a consequence of a dearth of atmospheric moisture for precipitation—a dearth caused by glacial growth rather than by freezing of the Arctic Ocean surface as a result of the lowering of sea level below some critical sill depth, as originally postulated.

Our purpose in this article is to present the revised theory, including a discussion of the time of onset of glaciation and a consideration of the heat budgets of ice-covered and ice-free states of the arctic sea surface. Consideration of the heat budgets is necessary for any estimate of the likelihood that an ice-free condition of the Arctic Ocean could have been maintained.

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Theory of Polar Migration

Despite arguments on both sides of the question, there is a large quantity of observational data that strongly supports the idea of progressive polar wandering during geologic time. A full development of the total argument in support of such migration is beyond the scope of this article, but it may be noted that the strongest evidence comes from such diverse areas as Bowen's paleotemperature studies (*2*), Lotze's data on the distribution of evaporites (*3*), paleobotany [for example, Andrew's summary (*4*)], and studies of paleowind directions by Opdyke and Runcorn and by Shotton (*5*). Perhaps the most cogent evidence is that of paleomagnetism. If, as is generally assumed, the earth's magnetic field is primarily a dipole field with the magnetic axis close to the rotational axis, changes in the positions of the magnetic poles would indicate changes in the positions of the geographic poles. According to the paleomagnetic data, such as are summarized by Irving (*6*), the north magnetic pole entered the Arctic Ocean early in the Tertiary period and reached its present location during the Miocene epoch.

In relating the hypothesis of polar wandering to the initiation of the Pleistocene Ice Age, we explained (*1*) the strong zonation of global climate, so different from the warm, equable climates of earlier ages, as the result of thermal isolation of both polar regions. If this theory be generalized to include the Permo-Carboniferous Ice Age, one finds that no such thermal isolation would have occurred in the Northern Hemisphere, since the paleomagnetic pole would have been located in the mid-Pacific Ocean at that time. With the exception of parts of India, Permo-Carboniferous glaciation was restricted to the continents of the Southern Hemisphere. All such glaciation, except for that on Antarctica, was spread over land areas from close to the equator to latitudes no higher than about 40°S. We wish to reemphasize the classical idea, from the theory of polar wandering, that, on the basis of present geography, it does not seem possible to explain the glaciation of the low-latitude lands of the Southern Hemisphere in any way that does not require the hypothesis of vaster glaciation of the widespread high-latitude lands of the Northern Hemisphere than is indicated by the evidence. No factor affecting solar radiation would have been restricted to a single hemisphere for geologic intervals.

Onset of Glaciation

If the geographic poles reached their present positions in the Miocene, as indicated for the paleomagnetic poles, there was, according to our theory, an apparently excessive lag before the commencement of Pleistocene glaciation. But the geographic poles may have reached their present locations later than is indicated by paleomagnetic evidence. The exact length of the lag cannot now be specified because of uncertainties concerning both paleomagnetism and the time of onset of glaciation.

Although the paleomagnetic evidence for polar wandering is strong, there is still a considerable lack of precision concerning particular polar locations. Both Irving (*6*) and Rezanov (*7*) describe serious inaccuracies in the methods used; to these inaccuracies Rezanov attributes errors of 2000 kilometers in the proposed locations of the paleopoles. If these errors involve systematic factors, such as significant nondipole components of the magnetic field, they lead directly to errors in the times proposed for pole positions as well as errors in the locations.

As regards the timing of Quaternary glaciation, it is now well known from the fossil record that a cooling of the middle and upper latitudes began early in the Tertiary. Until quite recently it was believed that the glacial threshold was crossed about a half million to a million years ago. However, Ericson *et al.* (*8*) described ice-rafted detritus in the Pliocene section of a core from the southern Indian Ocean. In further studies of cores from the Southern Ocean, Conolly and Ewing (*9*) show that the ice rafting began abruptly in the Pliocene and was continuous thereafter; these latter studies support strongly the conclusion of Ewing and Donn (*1*) that Antarctica must have undergone continuous glaciation from the beginning of the glacial epoch. Krinsley and Newman (*10*) have demonstrated the presence of glacial textures on sand grains associated with the coarse detritus in one of the Indian Ocean cores (V 16-66), thus proving that the coarse material was ice-rafted, as assumed by the earlier investigators. Others [for example, Bandy, and Jenkins (*11*)] have questioned the placing, by Ericson and his associates, of the Plio-Pleistocene boundary at "250,000 years" about the glacial detritus, and Bandy proposes a Miocene-Pleistocene boundary for this level, thus interpreting the presence of a significant disconformity in the core.

The initial glaciation of Iceland is now thought to have occurred much earlier than the date heretofore accepted for the beginning of North American glaciation. Tills of successive glaciations on Iceland are often well preserved by extrusive sheets of lava which prevent the erosion and deep weathering that destroyed so much of the North American and Eurasian glacial record. Through correlations with continental deposits, based on paleomagnetic reversals in lavas, Rutten and Wensink (*12*) and Wensink (*13*) appear to have established pre-Quaternary glaciation in Iceland. Wensink has dated the earliest glaciation in northeast Iceland at about 3.1 million years ago (*14*). And, in southeastern Iceland, Jonsson (*15*) described tillites beneath 1000 meters of basalt which he considers older than Pleistocene, a view supported by Schwarzbach and Pflug (*16*), who suggested a possible Miocene age, from results of a palynological study of lignites also contained in the basalt.

Apparently cooling was continuous during the late Tertiary, with glaciation commencing at a certain temperature threshold. The time of this threshold is still not sufficiently well established to permit correlation with the equally uncertain time of the north pole's reaching the center of the Arctic Ocean. It may well be that the onset of glaciation was earliest in Antarctica, in view of Antarctica's central position relative to the pole and to the large surrounding ocean bodies supplying moisture. The glaciation of Antarctica would have had a widespread effect, in view of the large amount of cold bottom water generated in that region. For example, the cold antarctic water now spreads northward to at least 35°N in the form of cold bottom water with temperatures close to 0°C (*17*) and thus exerts a strong effect on global temperature regimes. Additional significant cooling effects would also have resulted from the increased albedo of Antarctica, all the more important because of the glacier's high elevation, which would in itself have increased radiation loss, and from the eustatic lowering of sea level, equivalent to a temperature decrease of about 0.5°C. It is difficult to estimate the possible distribution of glaciers prior to the development of the antarctic ice cap until the global temperature effect of this ice cap can be appraised quantitatively. We cannot, for example, form an opinion about the occurrence of pre-Quaternary glaciers in northeast Asia, despite the proximity of this region to the track of the north pole.

Theory of the Open Arctic Ocean

The suggestion that the Arctic Ocean was once free of ice comes in part from a comparison of regions now deglaciated but once ice-covered with regions still mantled with ice sheets. The most obvious contrast is that between northern Canada and Siberia on the one hand and Greenland and Antarctica on the other; in this case, the difference seems to depend on the availability of moisture for precipitation. Northern Canada and Siberia, with an annual precipitation of 10 to 25 centimeters, are deserts at present, because of the ice-covered Arctic to the north and the large, often mountainous, land areas to the south, whereas Greenland and Antarctica have ice caps about as thick as those they had in glacial times (see, for example, *18*). Both Greenland and Antarctica are surrounded completely, or almost completely, by relatively warmer open ocean areas that provide moisture for precipitation. Admittedly, present-day precipitation is relatively low, but this results from the high elevation and the low temperature of the ice caps. Snowfall, which is currently adequate to maintain the ice at equilibrium thickness, would probably increase considerably in the absence of the caps.

In support of the precipitation theory of glacial initiation, Lamb (*19*) notes that during the cold episode of the "Little Ice Age" (1550–1850) no important waxing of the main polar ice caps occurred. Also, during both the recent warm period and the warm period of about 2000 B.C., the ice on Greenland and on Jan Mayen Island appear to have advanced (*20*). Recently Chemekov (*21*) concluded that the principal source of moisture in the glaciated monsoon regions of the Soviet Far East was the moist summer monsoon.

Despite these observations, Kraus (*22*) has argued that lower summer temperature rather than increased precipitation is the more critical factor in initiating glacial growth. However, snow cover makes its own climate. Increased winter snow cover from an open Arctic would cause a lowering of temperatures in subsequent months, as already documented for the middle latitudes. Namias (*23*) showed that temperatures over the central United States in mid-February to mid-March 1960 were as much as 6°C below expected values because of increased reflection due to a somewhat extended snow cover during that time. Similarly, in December 1962 the snow cover extended several degrees further south than was normal for the northern United States and large parts of Europe and Asia. Adem (*24*) then demonstrated that temperatures for January 1963 were as much as 6°C and 10°C below expected values for North America and Eurasia, respectively. Apparently, increased winter snowfall in the Arctic, which persists well into the spring, would in itself result in cooler summers and accelerate the development of a glacial regime.

Although we formerly proposed that an ice-free Arctic Ocean could supply the moisture necessary for most of the growth of continental glaciers in the Northern Hemisphere, this proposal must now be modified in the light of theoretical and empirical data given in following sections. We postulate now that the open Arctic provides the moisture necessary to initiate glacial growth to some critical size in high latitudes. Mechanisms for the rapid expansion of an ice sheet beyond a critical size have been given in detail by Brooks (*25*) and Weertman (*26*). The refrigeration of the atmosphere and oceans which would result from ice-sheet growth plus the lowering of sea level would, as explained below, cause the Arctic Ocean to freeze over sometime during the glacial stage and possibly soon after the critical size of the ice sheet had been reached.

In North America, the large moisture source from the south was available to support continued glacial expansion to about the 40th parallel, where warming from the south produced a glacial front in dynamic equilibrium with fluctuations of climate. In Siberia, the central desert restricted glacial growth to the arctic fringe, which was nourished only by the ice-free Arctic Ocean. The latitude (about 60°N) to which the Siberian ice extended may be a clue to the size of an ice sheet that would result from an open Arctic alone.

Termination of a Glacial Stage

It seems easier to turn glaciers on than off. The cause of glacial retreat appears to be a more subtle combination of factors than the cause of glacial growth. The explanation may well lie in the pronounced temperature decrease of the surface waters of the North Atlantic Ocean and in the lag between the retreat of continental ice sheets and the warming of these waters.

The disposition of ice sheets in the Northern Hemisphere indicates that the principal sources of their moisture were the North Atlantic and hypothetical open Arctic oceans. With the freezing of the latter, the North Atlantic became the chief supplier of moisture, although the Pacific was certainly the source of moisture for the alpine and piedmont glaciers of western North America. According to paleotemperature analyses of deep-sea cores by Emiliani (*27*) and by Rubin and Suess (*28*), a cooling of from 6° to 18°C took place in the surface waters of the North Atlantic Ocean. A reasonable estimate for the resulting temperature of these waters would be 10°C below the present mean (about 15°C). This amount of cooling would have lowered the vapor pressure by about 50 percent, and this, in turn, would have resulted in a great decrease in the rate of nourishment of the ice sheet. Flohn (*29*) has calculated that in the tropics and subtropics the temperature decrease would have been 4°C, with a resulting decrease of evaporation by at least 20 percent of present values.

At the time of furthest advance, the ice sheets would have been in a state of sensitive equilibrium between their own cooling effects on the one hand and the effects of low-latitude warming and greatly reduced moisture supply on the other. Retreat could have commenced from a combination of causes. The continued cooling of the oceans would have continued the decrease in rate of nourishment beyond the equilibrium value. Further warming of the marginal regions of the stationary ice sheet would have resulted from the increased absorption of radiation by the moist zone beyond the ice, because the albedo of wet soil is half that of dry soil (*30*). The importance of this effect is emphasized by the observations, summarized by Kondrat'yev (*31*), that irrigation increases the local radiation balance by 20 percent for moderate climates, 40 percent for steppes, and 60 percent for semideserts. To this warming effect would have been added the increasing heat absorption of the "dirty" stagnant marginal ice. Once retreat began, the warming effects would have continued while the moisture supply would have remained at a low level.

For glacial retreat to be total, it is necessary for a significant lag to occur between the warming of the ocean and the beginning of retreat. Such a lag appears to have occurred at the end of the Wisconsin (Würm) stage. There seems to be general agreement among European and American geologists that maximum glacial advance occurred about 18,000 to 20,000 years ago (see, for example, *32*), and that it was followed by a retreat stage with minor or local readvances. Although the evidence is far from complete, glacial retreat on land is also indicated by the rise in sea level which began, according to the summary and interpretation of Farrand (*32*), about 19,000 years ago and reached approximately the present level 6000 years ago. Farrand's critical analysis also leads to the conclusion that fully half of Wisconsin glacial ice had vanished by 13,000 years ago.

Paleotemperature analysis of deep-sea cores, based on the principle of the O^{18}/O^{16} ratio, as formulated by Urey (*33*) and developed by others (*34*), shows that Atlantic surface temperatures declined almost continuously until about 13,000 years ago (see *27*, *35–36*). Broecker and his associates (*37*) also concluded, from a study of climate chronology, that ocean surface temperature rose sharply after 15,000, and probably close to 12,000, years ago. Although the core data indicate a very rapid initial rise of temperature, the curves for temperature relative to time (*36*) show that the rise to interglacial temperature levels was not completed until about 2000 to 3000 years ago.

Thus, by the time the ocean surface temperature increased sufficiently to provide a significant increase in precipitation, both the North American and Scandinavian ice sheets would have shrunk too much to benefit. According to Weertman's theoretical analysis (*26*), rapid shrinkage would have occurred after retreat to some critical size—possibly that which required Arctic Ocean moisture for initial growth. In support of this argument, Farrand (*32*) concluded, from empirical evidence, that the rate of shrinkage increased after 11,000 years ago.

So long as the observed lag in oceanic warming is systematically related to glacially produced climatic effects, the mechanism proposed can be generalized to fit the termination of earlier glacial stages. Inherent in this mechanism is the requirement for a reduction in the terrestrial heat budget in order for the lowered evaporation rate to be maintained. It was noted by Ewing and Donn (*38*) that the increased albedo of the glaciated and pluviated regions would produce a significant decrease in the average absorption of sunlight, hence in the terrestrial heat budget. According to the calculations of Budyko (*39*), a global cooling conservatively estimated at 7°C would have occurred. If the pluvial and glacial stages were similar, or approximately so, the increased albedo from cloud cover in the pluviated regions (*38*) would have about doubled this cooling. The cooling effect from an increased albedo has also been noted by Milankovitch (*40*), Soergel (*41*), and Emiliani and Geiss (*42*) in their investigations on climate change.

Farrand (*32*) summarizes evidence from different regions, both glaciated and nonglaciated, that the trend of air temperatures matched that of ocean temperatures, the warming becoming established thousands of years after ice-melting began. Thus, deglaciation commenced well before any observed warming of the oceans and atmosphere —another indication that, of the temperature and precipitation factors which control the growth and decline of ice sheets, a precipitation factor must have been primarily responsible for glacial decline, just as has been postulated for glacial growth.

The lag in the warming of the ocean surface is probably a consequence of several factors related to our model. (i) The present rate of overturn of the Atlantic deep water, on the order of a thousand years (*43*) would certainly be shortened by a decrease in surface temperatures of perhaps as much as 10°C from the present mean of about 15°C. (ii) At the height of glaciation, upwelling and consequent surface cooling would reach a maximum, for two reasons: the stable, warm, shallow layer on the continental shelves would be withdrawn, and the force of surface winds would be increased, from the effects of the equatorward contraction of the zonal circulation (*44*). (iii) The albedo effects of cloud cover over pluviated regions remote from North Atlantic influence —a cover which persisted in the American west, at least, for several thousand years after glacial retreat began—would combine with similar albedo effects of the retreating ice to prolong the lowered terrestrial heat budget consequent upon the increased planetary albedo referred to above.

We wish to reemphasize our conclusion, also reached by Emiliani and Geiss (*42*): if the waning of continental ice sheets was triggered by an increase in available insolation (an increase related to changes of the earth in its orbit, a fluctuating solar output, volcanic dust clouds, or variations in the gaseous components of the atmosphere), then the warming of the oceans and atmosphere should have occurred before such melting, rather than after it.

That this is the case can be appreciated from a simple calculation that indicates the changes to be expected from an increased heat input. The chief factors are the albedo of ice and water, 70 and 5 percent, respectively (or an absorption of 30 and 95 percent, respectively); the latent heat of fusion of ice (80 calories per gram); the latent heat of vaporization; and the high latitude of the ice sheets. For a given increase in radiation reaching the earth's surface, the ratio of the time required for warming of the oceans to the time required for melting of the ice can be estimated to a good approximation. If the largest of the ice sheets, the Laurentide, be considered to have a mean thickness of 2.5 kilometers (*45*), then the time required for melting of the ice, for a radiation input of x calories per square centimeter per day and the values given above for albedo and heat of fusion, is

$$\frac{2.5 \times 10^5 \text{ cm} \times 80 \text{ cal/cm}^3 \times 0.3}{x \text{ cal/cm}^2 \text{ day}} = \frac{6 \times 10^6}{x \text{ days}} \quad (1)$$

To estimate the time required for raising the temperature of a 100-meter layer of North Atlantic surface water by 10°C (the areas are not important), we must allow for the fact that the annual radiation received on a horizontal surface at the ground between latitudes 30° and 35° is twice that between latitudes 60° and 65° (*46*). We must also allow for the small retardation of radiational warming of the oceans which results from the loss of latent heat through evaporation. According to London (*47*), the present ratio for latent heat transmitted to the atmosphere relative to absorption of short-wave radiation is 0.093 to 0.237 (1:2.54). Thus, only 61 percent of the heat input should be used in raising the water temperature:

$$\frac{1 \times 10^4 \text{ cm} \times 10 \text{ cal/cm}^3 \times 0.95}{0.61 \times 2x \text{ cal/cm}^2 \text{ day}} = \frac{0.78 \times 10^5}{x \text{ days}} \quad (2)$$

When a ratio is formed of Eqs. 1 and 2, it may be seen that the time required for warming of the oceans by 10°C is about 1/80 the time required for melting of all the ice. The values of 10°C and 100 meters for rise in temperature and water depth are probably conservative in this calculation, and this fact probably offsets any increase in the ratio that would occur from significant horizontal interchange with cooler waters. Even when 500 meters is substituted for 100 meters, the warming of the ocean surface should precede melting of the ice. The fact that a strongly opposite effect occurred argues against a primary radiational control of glacial behavior.

Heat Budget of an Ice-Free Arctic Ocean

The argument that the arctic surface water was at one time ice-free must be examined to establish whether such a state could have been maintained. This examination can now be undertaken on the basis of data and results that became available during and following the International Geophysical Year (IGY). The results of a detailed study of this problem by Donn and Shaw (*48*), summarized below, are especially pertinent in view of the possibility that the present ice-pack shrinkage, described in a number of reports (*49*), might continue until the ice is completely gone. In order to appreciate the nature of the changes to be expected under ice-free conditions and to make valid assumptions on which to base the evaluation of critical parameters, one needs, also, a fairly complete analysis of the present polar heat budget. The region considered is the central ice-covered Arctic Ocean or North Polar Sea, which has an area very close to 10^{17} square centimeters.

Surface heat budget factors evaluated by Donn and Shaw are as follows.

1) Net short-wave radiation absorbed by the surface. This value is the difference between the total solar radiation incident on the surface and the percentage lost through the albedo of the surface.

2) The ocean-current heat flux—heat transported primarily from the North Atlantic and secondarily from the Pacific through the Bering Strait.

3) Long-wave (infrared) radiation from the surface—the major heat-loss process.

4) Heat lost from the surface to the atmosphere as latent heat in the evaporation process—a smaller but significant quantity.

5) The sensible heat loss, or heat lost by conduction from surface to air and, subsequently, removed by turbulent flux—also a small but significant quantity.

An evaluation of these factors for present conditions (Table 1, cols. 2 and 3) gives a small net heat balance of 0.1×10^{21} calories per year for the polar sea. Because this balance is within the limits of possible error it is not very significant and simply indicates a net heat balance of, or close to, zero.

Since the earth-atmosphere system, not the surface alone, is involved in the complete heat budget, for both present and ice-free conditions, the additional factors of heat gain through direct absorption of solar radiation by the atmosphere and heat loss to space at the top of the atmosphere must also be estimated. The difference between the heat loss to space and all of the polar heat sources described must be made up by the atmospheric advection

Table 1. Comparison of the annual surface heat balance of an ice-covered and an ice-free polar sea (in units of 10^{21} calories).

Components	Ice-covered		Ice-free	
	Gain	Loss	Gain	Loss
Net short-wave radiation absorbed	2.83		5.24	
Ocean-current heat flux	0.16		0.32	
Long-wave surface radiation		2.29		0.96
Evaporation (latent heat)		0.31		1.23
Sensible heat		.38		0.74
Balance	.01		2.63	

of sensible and latent heat from lower latitudes. The results of the calculations of Donn and Shaw for the present heat balance of the earth-atmosphere system in the north polar region are given in Table 2, columns 2 and 3.

The heat budget of an ice-free arctic surface involves changes in all the factors included in Table 1, as shown by the results of Donn and Shaw in columns 4 and 5. The major change—the increase in absorbed short-wave radiation—results from a decrease in the albedo of the polar sea from about 61 percent to 10 percent for ice-free conditions. The slight increase in ocean-current heat flux is based on a probably increased Arctic-Atlantic interchange, described elsewhere (*1*). The reduced loss of long-wave energy results from the increased greenhouse effect arising from an increased atmospheric moisture content and low cloud cover, as evaluated by Donn and Shaw (*48*). The increased cloud cover would also cut down, somewhat, the amount of short-wave radiation reaching the surface, an effect considered in calculating this value. The determination of the loss to the atmosphere of latent and sensible heat was based on mean conditions at Jan Mayen in the central Norwegian Sea.

The resulting positive balance of 2.63×10^{21} calories per year for the polar basin is of course somewhat tentative, being based on observational data which are the best available but are by no means complete, and on certain assumptions concerning how conditions would change if the central Arctic Ocean were ice-free. As it stands, the balance is about ten times the amount of heat necessary to melt all the arctic pack ice.

If the estimate is correct, this heat excess may indicate that the ice-free ocean was somewhat warmer than 0°C, the value used in the calculations. Or it may result from uncertainties in the values adopted, but even if the value is in error by a factor of 10, a positive balance remains. In a similar investigation, Budyko (*50*) concluded that the temperature of the polar air would be several degrees above zero in the absence of the pack ice.

As mentioned above, the combined earth-atmosphere balance was determined by Donn and Shaw. This determination is of particular importance in view of a possible strong negative effect of higher heat loss from the warmer cloud tops. The results in columns 4 and 5 of Table 2 show a larger total heat budget than that for present conditions—a consequence of the stronger surface absorption of solar radiation. They also show a smaller required advection of heat into the polar atmosphere. This is quite reasonable in view of the warmer polar sea and air, and permits a satisfactory heat balance to be achieved.

A striking result of this investigation is the finding that the magnitude of the radiation term as well as that of the terms for latent and sensible heat so exceed the ocean-current heat flux as to indicate that the Atlantic-Arctic interchange exerts little primary control on the arctic heat budget. The decrease in heat flux from the Atlantic by the fall of sea level below the submarine sill, described in our initial proposal (*1*), thus seems inconsequential as the main cause of the termination of a glacial stage. This result, together with the time variations of ocean surface temperature described above, led to modification of our theoretical model. The effect of the ocean currents at times of high sea level in an interglacial stage may be to provide the small heat-flux increment responsible for a slow melting of the arctic pack ice. Once the ice was melted, the strong radiation effect would lead to a strongly positive heat balance.

The decline of sea level during glacial growth would introduce a further factor tending to retard the refreezing of an open Arctic Ocean. At present, the Arctic is characterized by a very stable stratification resulting from the presence of the layer of cold water of low salinity and low density (arctic water) which overlies the slightly warmer, but more saline—hence denser—North Atlantic water. Surface runoff and North Pacific water, of relatively low salinity, which enters through the shallow, narrow Bering passageway, are the major contributors to this surface layer (*51*). Although the layer of arctic water is about 200 meters thick, a strong pycnocline occurs from about 50 to about 200 meters (*52*), resulting from a sharp increase in salinity in this zone. The values are such that convection from surface cooling tends to be restricted to this shallow 50-meter-thick water layer. With the build-up of circumarctic ice sheets, surface runoff would decrease and sea level would be lowered; the lowering of sea level would cut off the Bering Sea influx as well as increase the salinity (density) of the arctic water through concentration. As the contrast between arctic and Atlantic water diminished, convection would extend into the underlying, thicker water layer; some 850 meters of water would then have to be cooled before freezing occurred. Conceivably, the arctic water might be lowered out of existence and the warmer Atlantic water, with its higher heat content and relatively high temperature [at present 1° to 3°C (*52*)],

Table 2. Comparison of the annual heat balance of the earth-atmosphere system for an ice-covered and an ice-free polar sea (in units of 10^{21} calories).

Components	Ice-covered		Ice-free	
	Gain	Loss	Gain	Loss
Escape across the 300-millibar surface		14.40		15.65
Insolation absorbed in atmosphere	2.89		2.89	
Long-wave radiation from surface	2.29		0.96	
Latent and sensible heat from surface	0.69		1.97	
Surface heat excess			2.63	
Required heat advection by atmosphere	8.53		7.20	
Totals	14.40	14.40	15.65	15.65

would be exposed to the atmosphere. Although it is difficult to quantify this effect, it certainly appears that freezing of the surface will be retarded as the thicker and warmer Atlantic layer becomes more involved in convection from surface cooling.

The Freezing of the Arctic Ocean

The results of Donn and Shaw provide a theoretical basis for the view that an ice-free Arctic Ocean is the initiator of a glacial stage. But the growth of circumpolar glaciers would produce an increased heat loss from several factors, causing the ultimate refreezing of the polar sea.

If the circumpolar glacial area to be nourished by the Arctic Ocean is taken as 10^6 square kilometers (10^{16} square centimeters), then the evaporation of 1 centimeter of water from the surface of the polar sea (area, 10^{17} square centimeters) would provide 10 centimeters of liquid precipitation over this area. This moisture could easily provide a reasonable annual accumulation of 10 to 20 centimeters of snow and ice requiring only 1 to 2 centimeters of the liquid precipitation available. The annual latent-heat loss to the polar sea of nearly 6×10^{19} calories would be released to the atmosphere over the glaciers. Although some of this would be returned to the polar region by atmospheric advection, the total loss is still small compared to the large positive heat values associated with an open arctic.

The growth of a circumpolar ice sheet would, however, produce a greater heat loss from turbulent or sensible heat flux than is indicated by the values given in Table 1. Treated as an independent system, the heat loss over the open polar sea would be small because of the small air-sea temperature difference. But with the growth of circumpolar ice sheets, the advection of cold air over the relatively warm water would slowly increase. This effect, together with the effects of icebergs calved into the sea and latent heat loss, would cause the surface to refreeze. Although there is no reliable basis for estimating the turbulent-heat loss (even the present value is not too well known), an idea of its size can be gained from estimates of what the present turbulent loss would be in winter over open leads. According to the estimates of Vowinckel and Taylor (*53*), such loss from winter leads, when extrapolated to the polar sea, would be about 5×10^{21} calories per year. Probably this value would be lower with an ice-free sea having a glaciated perimeter because (i) annual air temperature over the glacial ice cap would be higher than present winter air temperature over the polar sea, and (ii) much of the cold air from the ice sheet would be advected southward as well as northward.

It seems certain that, with growth of the ice sheet, an increasing turbulent-heat exchange would occur until a value close to that given above was reached. Freezing of the surface would then occur, terminating the arctic moisture supply.

Summary

In view of the modifications described here, it may be appropriate to summarize the framework of our complete model.

1) The migration of the geographic poles to regions of thermal isolation caused a decline of temperatures in the middle and higher latitudes, during the Tertiary Period, culminating in the development of the present strongly zoned climate with high-latitude temperatures at the glacial threshold.

2) Continental glaciation probably began on Antarctica and persisted there throughout the Pleistocene Epoch, its presence causing further global cooling of both hemispheres.

3) In the Northern Hemisphere, continental glaciation was initiated in high latitudes by additional precipitation from an ice-free Arctic Ocean. The latter would have frozen over, possibly toward the middle of a glacial stage, when its relatively high heat budget would be offset by the cooling effect of the surrounding ice sheets. The southerly extent of glaciation, beyond the southernmost boundary of the influence of the open Arctic Ocean, was a function of the amount of moisture available from the south, as shown by the progressive shift of the glacial margin from about the 40th parallel in North America to the 60th parallel in Siberia.

4) At the time of glacial culmination, the temperature of ocean surface waters, for the North Atlantic in particular, would be lowered sufficiently to decrease the rate of evaporation and hence of precipitation over the ice sheets, which would then retreat, through the combined effects of decreased nourishment and increased warming of the margin.

5) The time lag necessary for total melting of the ice would be provided by the lag in the warming of the ocean surface, the time interval of about 5000 years for the North Atlantic at the end of the Wisconsin (Würm) stage thus being an important time constant in the glaciation cycle.

6) The next glacial stage would begin when the polar ice pack again vanished as a consequence of the small increase in ocean-heat flux which would result from the postglacial rise in sea level, or possibly from a small increase in radiation.

According to the model described, glaciation in the Northern Hemisphere is initiated by an increase in precipitation and is terminated by a decrease in precipitation. The hypothesis that initial temperature variations are causal factors in these changes appears to be invalid.

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Components of Skilled Performance

Human limitations of attention and memory are basic to the analysis of skilled performance.

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Since its inception, experimental psychology has been engaged in the task of describing the various component functions man performs in doing skilled tasks. Of particular interest has been the quantitative exploration of the limits of man's performance in each component function. Pioneer investigations concerned how fast a man can begin a response, how much he can see at a single glance, how much time is required for discrimination, and how much of what he sees is retained after a single exposure (*1*). More recently the same questions have been raised in a more general approach to the study of performance limitations in human beings (*2, 3*), which has included investigation not only of individual components but also of the interactions between components. This approach was called human performance theory by the late Paul Fitts, who did much to develop it in this country.

Under the influence of developments in communications engineering and computer science, recent studies in experimental psychology have employed much of the logic and language and some of the mathematics of information and communication theory. These influences are apparent in studies concerning the maximum rate of information transmission in human beings, limitation in the capacity for discriminating sensory information, the capacity of visual and auditory short-term memory stores, and the trade-off between speed and accuracy of responses (*2, 4*); all these studies incorporate the older interest in the limitations of man's capacities within the newer analytic framework. Occasionally the number and complexity of component functions, particularly in studies of intellectual performance, are so great that the psychologist turns to computer simulation as a technique for exploring the interaction of these functions (*5*). More typically, and with much the same goal, investigators have used traditional laboratory methods to measure the components of skill and to understand their interactions.

This article is concerned with the limitations of attention and memory in the performance of skills. Prior to the birth of experimental psychology, philosophers discussed limitations in the span of attention (the number of items to which a man could attend simultaneously) and in the memory span (the number of items a man could report after a single presentation) (*6*). The experimental analysis of these limitations was among the earliest undertaken by psychologists. This article begins with recent efforts to determine a channel capacity for man in simple tasks of information transmission. Although no general limitation to man's rate of processing information has been found, results of such experiments lead to techniques by which the amount of attention required can be controlled by varying the processing demands of the task. In the second section, I discuss use of these techniques to demonstrate that the rate of loss of information from a short-term memory system depends upon the processing capacity (attention) available during a brief period after presentation of the stimulus. In later sections I build upon this analysis to discuss the phenomena of interference and imagery within this general framework. In the final section reference is made to some applications of these principles in the study of familiar skills.

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