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A Theory of Ice Ages

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This article is a preliminary report of new ideas related to the origin of glacial climates; it is based largely on observations made during the last 20 years. Glacial climates pose two problems: (i) the striking alternations during the Pleistocene epoch of glacial and interglacial stages and (ii) the even more striking change from the warm nonglacial climate, which prevailed generally from the Permian to the Pleistocene, to the cold and glacial conditions of the Pleistocene and Recent.

If it is difficult to answer the second question, it is even more difficult to solve both problems on the basis of a single theory. The present study (*1*) offers an explanation for the alternations in climate during the Pleistocene and proposes an explanation for the change from nonglacial to glacial climates.

Pleistocene Glacial and Interglacial Stages

First we wish to develop the following principal points of the glacial-interglacial theory.

1) The melting of an Arctic ice sheet (such as exists at present) would increase the interchange of water between the Atlantic and Arctic oceans, cooling the North Atlantic and warming the Arctic and making it ice-free, thus providing an increased source of moisture for the polar atmosphere.

2) Two factors would then favor the growth of glaciers: (i) increased precipitation over arctic and subarctic lands and (ii) changes in atmospheric circulation, the latter also resulting from the warmer Arctic and cooler Atlantic oceans.

3) The lowering of sea level would greatly decrease the interchange of water between the Atlantic and Arctic oceans, which, together with the cooling effect of surrounding glaciers, would reduce Arctic surface temperatures until abrupt freezing occurred. The fairly sudden reversal of conditions favorable to glacial development would terminate the growth of glaciers abruptly.

4) As continental glaciers waned, the sea level would rise, causing an increased transport of surface waters northward until the Arctic ice sheet melted once again, completing the cycle.

5) Temperature changes in the surface waters of the Arctic and Atlantic oceans are thus the causes of, rather than the consequences of, the waxing and waning of continental glaciers.

Abrupt change in Atlantic deep-sea sediments. Using radiocarbon measurements, Ericson *et al.* (*2*) and Rubin and Suess (*3*) have established dates as far back as 30,000 years ago for cores of deep-sea sediments. Using paleotemperature measurements based on the oxygen isotope ratio, Emiliani (*4*) determined the temperature of the water in which pelagic Foraminifera lived; his findings covered a time interval represented by the longest cores available. Suess (*5*) then combined these two sets of results by plotting the radiocarbon ages for three deep-sea cores from the equatorial Atlantic and Caribbean against the paleotemperatures of Foraminifera tests. The resulting graph may be interpreted as showing a temperature decline of 1°C per 11,000 years for the interval from 90,000 to 11,000 years before the present. Temperatures then began an abrupt increase at a rate of about 1°C per 1000 years from 11,000 years ago to a few thousand years ago. For the last few thousand years, temperatures have remained about as high as the maximum value that was reached during all Pleistocene interglacial stages (see Emiliani, *4,* Figs. 2 and 3).

The curve given by Suess for Core A 172-6 shows the abrupt temperature change beginning about 16,000 years ago as compared with the change shown at 11,000 years in the other cores. Since the time scale for this core depends on only three points, considerable interpolation is required, and since Emiliani shows that a strong solution of carbonates occurred in a number of places, linear interpretation is likely to be unreliable.

In addition, faunal studies by many investigators show that a well-marked change in most cores indicates the termination of the Wisconsin age. In 1935, Schott (*6*) described the faunal break in many equatorial Atlantic cores, which was later noted in more recent longer cores—for example, by Bramlette and Bradley in 1940 (*7*), Phleger, Parker and Pierson (*8*), Ovey (*9*) and Schott (*10, 11*). Most recently, radiocarbon measurements on a number of cores described by Ericson and Wollin (*12*) from the Atlantic Ocean and Caribbean Sea show that this characteristic break (*13*), marking a change from cold to warm pelagic fauna, occurred 11,000 years ago (*2*). Cores taken in the Gulf of Mexico show a similar faunal break (*14*), although as yet no quantitative temperature or time measurements have been made. However, on the basis of the fauna change, it is possible to correlate the break in the Gulf of Mexico with that described in the Atlantic Ocean.

Cores from the Gulf of Mexico. Many sediment cores 30 to 40 feet long have been taken on the Mississippi Cone (*15*), which spreads over most of the deeper part of the Gulf of Mexico from a vertex just off the Mississippi Delta. These cores, which show a layer up to 2 feet thick of foraminiferal lutite, indicating warm water, overlie with a sharp transition a layer of essentially unfossiliferous lutite and silt, the bottom of which was never reached. Pending radiocarbon measurements, it seems reasonable to extrapolate the date of 11,000 years ago for the bottom of the foraminiferal layer. In cores taken on the nearby Sigsbee Knolls, which rise 20 fathoms above the cone and above the reach of turbidity

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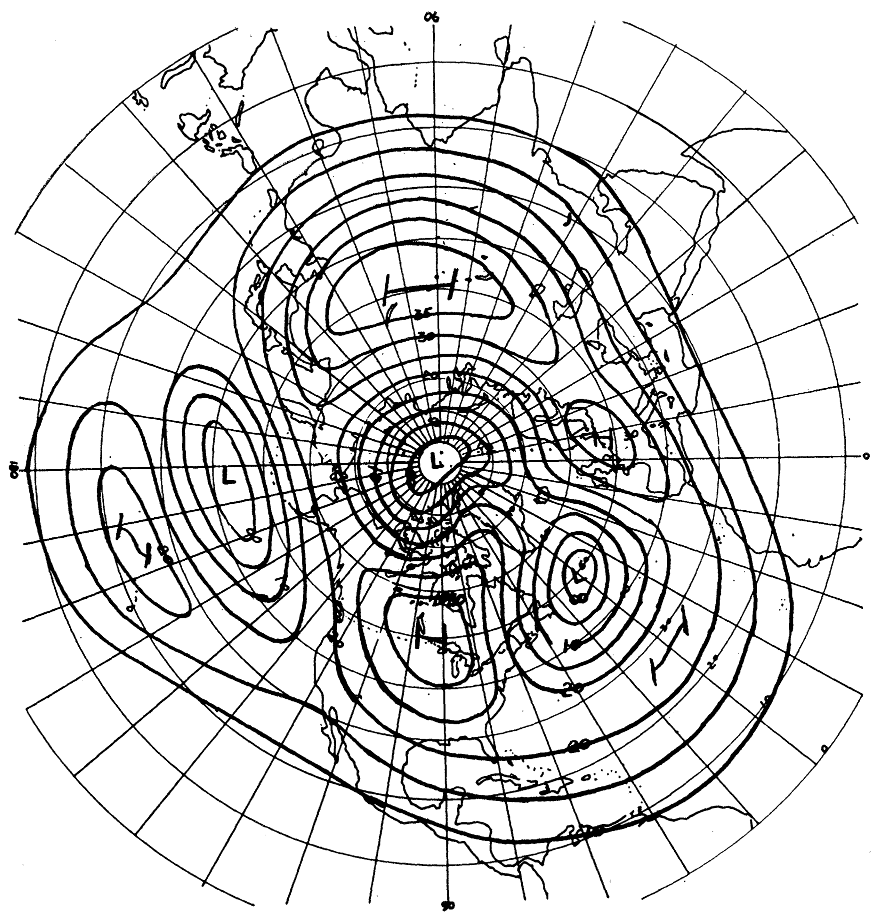

Fig. 1. Chase's map of hypothetical pressure pattern during a glacial age with an ice-free Arctic Ocean. Air motion is clockwise about high-pressure areas (*H*) and counterclockwise about low-pressure areas (*L*). Continental highs correspond to present-day cold winter situations.

currents, Foraminifera of the cold-water type are abundant throughout the silty layers (*14*). It is concluded that the extreme scarcity of Foraminifera in the silty layer of the Mississippi cone is due to dilution from a great influx of clastics in Wisconsin time. The sediments give no evidence of any climatic change except that 11,000 years ago.

Further, the beginning of rapid postglacial rise in sea level is indicated by the abrupt decrease in clastic deposition on the Mississippi cone about 11,000 years ago, when the drowned rivers retained their clastic sediments instead of discharging them into the Gulf (*15*).

The result of a very recent investigation of turbidity current deposits made by Heezen and Ewing (*16*) shows that an abrupt rise in sea level must have taken place about 11,000 years ago; this event is also taken to mark the close of the Wisconsin glacial stage.

Conclusions from Atlantic and Gulf data. On the basis of these data, we regard 11,000 years ago as the date of the most recent significant temperature change in the Atlantic Ocean, and also as marking the end of the Wisconsin glacial stage. Additional breaks in isotopic temperatures (*4*) and faunal types (*7, 8, 11, 12*) occur in many of the Atlantic cores which penetrate most of the Pleistocene. We regard these as marking the transition from earlier glacial to interglacial stages.

The data show that this fairly abrupt increase in temperature in the surface layers of the Atlantic Ocean about 11,000 years ago was the most significant temperature change of the past 60,000 to 80,000 years, although similar changes occurred earlier in the Pleistocene. Because the beginning of glacial retreat which closed the last Wisconsin substage (Mankato) occurred about 11,000 years ago—for example, Flint (*17*)—it appears that the oceans became warm abruptly at the time retreat commenced and remained warm during retreat of the ice.

We propose to show that the temperature of the surface layer of the ocean, rather than external conditions, regulated the climate of the land. Specifically, we suggest that the alternating warm and cold stages of Pleistocene climate are the effects of fairly abrupt alternations between warm and cold conditions of the upper layer of the Atlantic and Arctic oceans. We are thus led to consider the cause of the pronounced fluctuations of the temperature of the Atlantic and Arctic oceans.

Arctic Ocean cores and the influence of the arctic. Three short cores (9, 14, and 16 centimeters long) and one long core (81 centimeters long) were taken in the deeper part of the Arctic Ocean by A. P. Crary and studied by D. B. Ericson. The upper 20 centimeters of the 81-centimeter core contain abundant Foraminifera (*Globigerina*), which decrease in the next underlying 10 centimeters. The long section below 30 centimeters consists of lutite, with granules and pebbles distributed sparingly throughout, and shows no *Globigerina* except for a few near the bottom. Several radiocarbon measurements on the Foraminifera of the 16-centimeter core (*18*) gave an age from 18,000 to 23,000 years. Other cores, collected elsewhere in the Arctic by Crary, show thin sediment zones above the foraminiferal layer. The presence of this upper foraminiferal zone, with no or only thin overlying sediment, indicates an abrupt end of conditions favorable to the growth of Foraminifera and suggests that the Arctic Ocean was open during the Wisconsin glacial stage. Further, the coarse fragments in the long lower section of the core are attributable to ice rafting under conditions that provided numerous icebergs free to move in open water. This condition would be met by an ice-free Arctic during Wisconsin time. The absence of *Globigerina* in the lower section of the core, except for the very bottom, can be explained by dilution by clastic sediments; and the presence of Foraminifera in the upper portion can be explained by a decrease in the amount of clastics. This is analogous to the similar, well-founded observations on cores from the Gulf of Mexico that were described in a preceding paragraph.

Based on the possibility that the Arctic Ocean can undergo both ice-free and ice-covered stages, we propose the following assumption: When the Arctic Ocean is ice-covered, surface temperatures in the Atlantic increase and continental glaciers decline; when the Arctic is open, surface temperatures in the Atlantic decrease, and continental glaciers develop. With this assumption in mind, let us examine the process by which an ice-free Arctic can bring about a glacial stage.

Consequences of an ice-free Arctic Ocean. Given an open Arctic Ocean, the resulting large increase in absorption of insolation is well known. The present circulation of water within the Arctic Ocean would be greatly increased (*19*) since the wind stresses would then be applied directly to the water. It is postulated that a marked increase in the interchange of water between the Arctic and Atlantic oceans would occur which would tend toward equalization of temperatures, cooling the Atlantic and warming the Arctic. With the added effect of greater absorption of insolation, the ice-free condition of the Arctic Ocean could be maintained against the cooling effect of increased evaporation.

The present mean temperature of the surface of the Arctic Ocean in January is – 35°C and in July, about 0°C. The vapor pressure of water (or ice) at 0°C is 4.6 millimeters of mercury; at 3°C, 5.7 millimeters; and for ice at – 30°C, 0.3 millimeter. The change to an ice-free condition would necessarily require an increase of winter ocean surface temperatures by at least 35°C. By extrapolating from the afore-mentioned data, it can be seen that the vapor pressure would increase by a factor of about 50 in the winter season, while the summer ocean surface temperature and vapor pressure would be only a little increased. The principal effect of an open Arctic is thus the providing of greater moisture during the long polar winter.

Although it is difficult to make a detailed analysis of the consequent changes in atmospheric and oceanic circulations and the results thereof, the following general conclusions seem reasonable.

1) The increased evaporation from an open Arctic Ocean, particularly in winter, would increase the precipitation over adjacent cold land areas, where lack of precipitation, rather than high temperatures, at present prevents the growth of glaciers (for example, Stokes, *20*).

2) The present polar high, with clockwise circulation, would be replaced by a low-pressure area with counterclockwise circulation because of the contrast between the warm water and the surrounding colder land. The resulting reinforced counterclockwise circulation of the Arctic Ocean would tend to increase further the interchange of Atlantic and Arctic waters, judging from the present North Atlantic circulation.

3) The semipermanent North Atlantic low would be displaced roughly 10 to 20 degrees southward. Increased zonal flow of air around the northern portions of this low would transport cool moist air over eastern North America. At the same time, the presence of relatively warm water on all sides of the continents would promote the development of cool continental highs.

4) Winter and summer conditions over the continents would become more similar as a permanent continental ice sheet developed, with a resulting migration of the present polar front southward.

5) The contrast between the cold northern land areas and the warmer open Arctic Ocean would result in a second, although weaker, polar frontal zone surrounding the polar low.

6) A second belt of storms would therefore be present, providing some nourishment for growing glaciers at the northern margin, in addition to the stronger nourishment at the southern margin.

7) The Atlantic Ocean would be cooled by lowered air temperatures induced by continental glaciers and by the abrupt cooling effect of increased interchange with the Arctic Ocean already mentioned.

J. Chase has given a general confirmation of these views in an analysis (see Fig. 1) that followed a presentation of the ideas of this paper at a colloquium at the Woods Hole Oceanographic Institution (*21*). His analysis is based on a study of extreme conditions shown on historical weather maps and represents hypothetical mean isobars during a glacial stage having an open Arctic Ocean.

Termination of a glacial stage. The glacial stage would be brought to an abrupt close by the development of a new Arctic Ocean ice sheet. Along most of an Atlantic Ocean profile, through either Iceland or Spitzbergen, the sill depth between the Arctic and Atlantic oceans is between 200 and 300 fathoms, and much of this is less than 50 fathoms, a depth generally accepted as the probable value for maximum Wisconsin decrease in sea level (see Fig. 2). When the lowering of sea level reached about 50 fathoms, a serious reduction in the interchange of water between these oceans would occur. The reduced inflow of warm Atlantic water, together with the cooling effect of the continental glaciers, would eventually allow a new Arctic Ocean ice sheet to form. The interchange of water would then be reduced to even less than its present-day value, owing to the reduced sea level. Thus, with the present radiation balance and the slow return to the current atmospheric circulation pattern, there would be no tendency to remove the Arctic Ocean ice sheet until sea level returned to at least its present position. A reversal of the phenomena described as consequences of an ice-free Arctic Ocean would consequently occur. Although gradual wastage of the continental glaciers would follow, the warming of the Atlantic surface water would be more rapid because of an abruptly diminished interchange with the Arctic.

If we consider the last glacial stage, we find that the studies of deep-sea cores indicate that 11,000 years ago is the date of the end of Wisconsin time. Furthermore, the end of Wisconsin glacial conditions in the ocean corresponds with, and according to our theory, caused the end of the Mankato substage on the con-

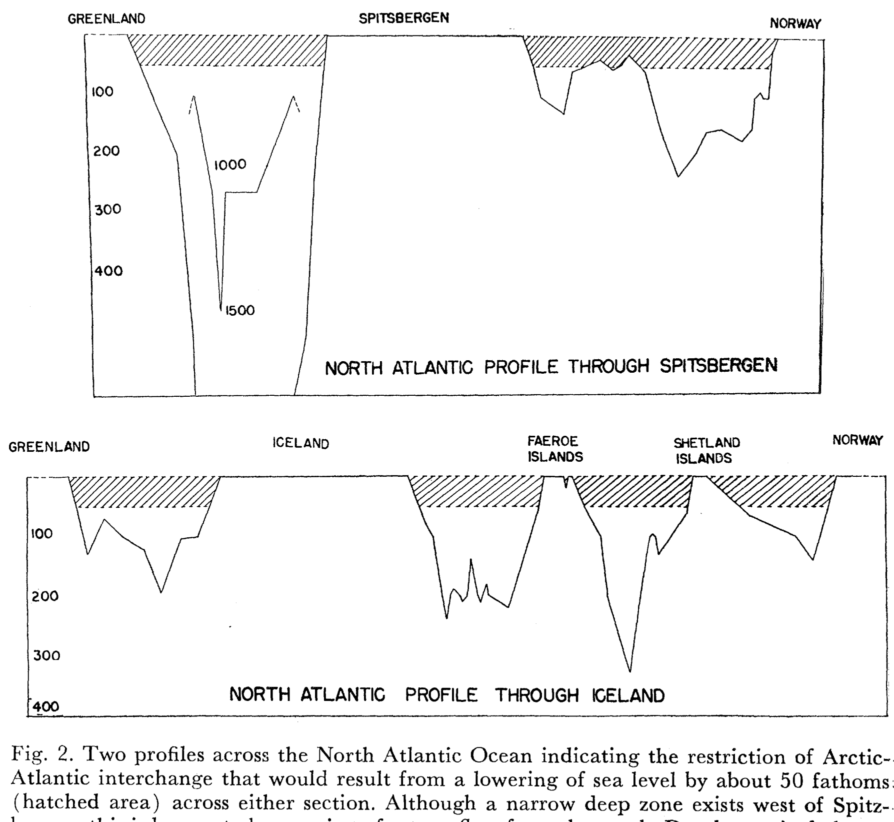

Fig. 2. Two profiles across the North Atlantic Ocean indicating the restriction of Arctic-Atlantic interchange that would result from a lowering of sea level by about 50 fathoms (hatched area) across either section. Although a narrow deep zone exists west of Spitzbergen, this is known to be a region of return flow from the north. Depths are in fathoms.

tinents. The glacial retreat between the Tazewell and Mankato glacial substage maxima (for example, Flint, *17*) is only a minor fluctuation.

The interglacial stage. The transition from glacial to interglacial conditions in the Atlantic Ocean would be simultaneous with the time of maximum continental glaciation (neglecting minor fluctuations). As the continental glaciers wasted, their cooling effects would diminish. The consequent rise in sea level would slowly enlarge the cross section of the channel between the Atlantic and Arctic oceans, providing an increase in the northward transport of warm water, as is occurring at present. Eventually a condition would be reached where the Arctic ice sheet would disappear.

Considerable evidence has been given by Berezkin (*19*) and by Crary, Kulp, and Marshall (*22*) which indicates that the Arctic Ocean has been warming recently. If that trend continues, open water over the entire Arctic Ocean might occur within a few centuries, with consequent glaciation in northern latitudes.

The presence of five temperature maxima, marking past interglacial stages, all at about the same temperature as the present (*4*) is strong evidence that an internal, self-regulating mechanism controlled the climate during the Pleistocene. Emiliani's graph of temperature versus time (*4*, Fig. 3) gives compelling evidence of oscillations of the system between two quasi-stable states, with the significant external conditions remaining constant throughout. This implies that present temperature is at the maximum value expected for an interglacial stage and that a decrease in temperature marking the onset of the next glacial stage may be expected within some few thousands of years.

In describing Pacific cores, Emiliani notes (*4*, p. 561) far less conspicuous temperature variations than in cores from the Atlantic. He explains this on the basis of greater vertical circulation in the Pacific, which seems to be a rather ad hoc solution. The observed uniformity in Pacific temperatures, however, is an expected consequence of the theory proposed here, in which strong temperature changes should be limited to the Atlantic and Arctic oceans. These observations also imply that some mechanism, involving only the Atlantic and Arctic oceans, is the most reasonable solution for the Pleistocene climatic variations.

Interpretation of Wisconsin glaciers. Our theory provides a new explanation for the Scandinavian and Siberian ice sheets. According to Flint (*23*), this sheet had a maximum thickness of about 10,000 feet, tapering off strongly to the north and east, and less strongly to the south. The combined lateral extent was from about 5°W at the British Isles to about 110°E at the Taimyr Peninsula. In view of the long continental path and the prominent mountain barriers to the south and west, it seems difficult to imagine nourishment from storms arriving from these directions. However, nourishment from the north would be provided by an ice-free Arctic Ocean, but would be almost impossible with the ice-covered ocean usually assumed for the glacial age. The steep north slope of this ice sheet further supports the theory that the source of precipitation was to the north.

The Laurentide ice sheet, which covered nearly 5 million square miles at the Wisconsin maximum (*23*), extended westward to meet the Cordilleran glaciers, and eastward to a line seaward of the present Atlantic coast, with its southern boundary along the Missouri and Ohio rivers. The maximum thickness has been estimated by Flint (*23*) to be about 10,000 feet. Although the northern boundary is not well known, it has been assumed to be thin, but recent observations by G. Hattersly-Smith (*24*) give evidence of very severe glaciation on Ward Island and northern Ellesmere Land at about 83°N. Here again, as with the northern and western margins, it is difficult to explain the sources of nourishment on the basis of present-day circulation and an ice-covered Arctic Ocean. However, the modified circulation described here provides for sources of precipitation from the Atlantic and the Arctic oceans, in addition to that coming from the south.

Finally, it is well known that the areas of the northern hemisphere covered by Pleistocene glaciers are centered roughly at the northeastern coast of Greenland, near the strait through which Atlantic and Arctic waters interchange (see, for example, Flint, *20*, plate 3). For the most part, glaciation in other areas was minor and was controlled directly by mountains. The distribution of Pleistocene glaciers again indicates the strong influence of both the Arctic and North Atlantic oceans on Pleistocene continental glaciers.

Climatic optimum. Evidence for open water in the Arctic Ocean in post-Wisconsin time has been accepted by many writers (for example, Brooks, *25*) and attributed to the "climatic optimum" or "thermal maximum" which many climatologists believe prevailed during the long interval from about 7000 to 2500 years before the present. The evidence is found in part on islands and remote shores where correlation with established chronology is difficult. We suggest that this evidence for an ice-free Arctic pertains to the open Arctic we have postulated for Wisconsin time rather than to the climatic optimum.

Other evidence for a climatic optimum is found further south on the continents, where it is correlated reliably with post-Wisconsin chronology. Although the climatic optimum is correctly dated here, we believe that it is a minor climatic fluctuation because it left no conspicuous evidence in marine sediments (*4*, *12*). Also, according to Fisk (*26*), there is no evidence of higher sea level than the present in the Gulf of Mexico during all of post-Pleistocene time.

Early man in the Americas. The facts about early man in the Americas support the idea of an ice-free Arctic during Wisconsin time and hence during earlier glacial stages. According to recent prevailing opinion—for example, Eiseley, (*27*)—early man reached Alaska from Siberia in great numbers during late Wisconsin time. The usefulness of the accepted land bridge between Siberia and Alaska would have been very limited if the Arctic Ocean had been ice-covered and the climate far colder than at present. The Denbigh Flint complex (northwestern Alaska) has been estimated from geologic correlations to correspond to warm periods either earlier than 12,000 years ago or about 8500 years ago (*28, 29*). Based on direct observations of the Denbigh flint work, Giddings (*29*) concludes: "The Bering Strait region was already a culture center at the time of deposit of the Denbigh flint layer." Giddings further notes "that most of the early flint techniques were distributed primarily on a broad band centering at the Arctic Circle; they seldom strayed south."

We believe that these observations refer to the time of the relatively warm and open Arctic Ocean prior to 11,000 years ago. The implication of a long-established culture in the arctic region conflicts strongly with the conventional concept of a Wisconsin ice sheet continuous from the North Pole to the Ohio River. If the Arctic Ocean were open in Wisconsin time, we should expect evidence of settlements along most of the shores of the Arctic, contemporaneous with those in Alaska. Giddings (*29*) has already pointed out a similarity between cultures for the Denbigh complex and settlements in northern Siberia.

About 11,000 years ago, the break-up of the ice permitted such rapid migration of Arctic population southward that the southern tip of South America was reached in a few thousand years (*27, 30*). The initial avenue from Alaska was the high plains east of the Rocky Mountains (*27, 31*), which would have no mountain barrier if it commenced in the low unglaciated area north of the Brooks Range and fronting on the Arctic

Ocean. Following glacial retreat at the close of the Wisconsin stage, the route along the high plain east of the Rockies would have opened, while that from northern Siberia would have closed as sea level rose and ice formed in the Arctic Ocean. Thus, as early man migrated southward, continued migration from northern Siberia was cut off.

Initiation of Pleistocene Glacial Climate

Although the theory we have presented attempts to provide an explanation for the alternations of climate during the Pleistocene epoch, it cannot give an explanation for the initiation of cold Pleistocene climate. A solution to this problem is offered now.

Reconsideration of the hypothesis of pole-wandering. Following the recognition of the extent and distribution of Pleistocene glaciers, many scientists sought an explanation of glacial climates in terms of major shifts in the positions of the poles. Much of the early work was summarized in 1883 by Hann (*32*), who believed that great secular changes in climate could only be accomplished by changes in the earth's axis of rotation. Kelvin and other physicists demonstrated that significant pole shifts would be impossible in view of the accepted evidence for high rigidity of the earth, thereby directing most subsequent studies toward alternative explanations. However, although they used different bases for their hypotheses, Köppen and Wegener (*33, 34*) and Milankovitch (*35*) never abandoned this idea.

In recent years attention has again been directed toward this hypothesis as it became clear that the earth could not be considered as a completely rigid body. Thus, Vening Meinesz (*36*) concluded that, "The forces causing tectonic orogeny which are probably exerted by sub-crustal currents must have been amply sufficient for a shift of the poles," and he assumed a pole shift of many degrees as the basis of his explanation of the major fracture pattern of the earth's crust. Runcorn (*37*) indicated that the earth's surface could undergo large displacements relative to the interior as a result of convection currents. In considering the direction of magnetic fields indicated by studies of paleomagnetism, Runcorn (*38*) believes that the variation in these fields could be fully explained by pole wandering.

Using a different approach, Jardetzky (*39*) recently reevaluated the work of Milankovich, concluding ". . . there was possible a slow secular displacement of the crust in space, which was progressive during all geologic periods. The cause of the rotation of the crust is the existence of a moment of centrifugal forces acting on the crust and due to the asymmetry of the distribution of masses in the outer shell."

The possibility that adequate forces exist to produce relative movement between the earth's surface and the interior has led us to reopen the question of the effects of pole wandering on secular changes in climate. It should be noted that the poles wander, according to present conception, in a relative sense. The differential movement between an outer shell and the interior results in different points on the surface assuming the positions of the poles.

Climatic consequences of pole migration. The poles are presently located in positions of extreme thermal isolation, in marked contrast to the conditions that would prevail if both were in the open ocean. If the North Pole were located in the North Pacific (for example, 35°N and 180°W) and the South Pole at the antipodes of this, in the South Atlantic Ocean, the free interchange of water with the polar regions would preclude formation of polar ice caps. The free interchange would further tend to equalize temperature extremes both geographically and seasonally. A resulting weak and uniform latitudinal temperature gradient would occur, in contrast to the present zonality. This kind of climate must have prevailed between the Permian and Pleistocene glaciations (and probably during the long intervals between other glacial periods), according to inferences made from the geologic record by all authorities.

Based on different investigations, Kreichgauer (*40*), Köppen and Wegener (*33*), Milankovich (*35*), Köppen (*34*) and Creer *et al.* (*41*), have all placed the North Pole in the North Pacific Ocean for a long interval beginning with the Cambrian. Although Milankovitch gave no dating, the other investigators estimated that the pole arrived in the Arctic Ocean during the Tertiary. On the basis of the worldwide distribution of corals of various ages, T. H. Y. Ma (*42*) concluded that sudden displacements of the solid earth shell with respect to the interior occurred. He also located pre-Cretaceous pole positions at distances of more than 90 degrees from their present positions in order to reconcile the fossil record with the appropriate climate, and concluded that abrupt shifts of the earth's crust during the Tertiary then carried the poles to their present locations. From studies of rock magnetization, Hospers (*43*) concluded that pole migration since Eocene time could have amounted to 10 degrees. It is proposed here that the migration of the poles from an open-ocean environment to the thermally isolated arctic and antarctic regions resulted in the change from the warm equable climate to the glacial climates of the Pleistocene.

Assuming that the North Pole migrated into the Arctic Ocean, the cooling effects of high latitudes would have become concentrated in this region owing to the isolation of the Arctic from the other oceans. In the same way, the migration of the South Pole from the freely circulating southern oceans to the Antarctic continent would have concentrated cooling effects over the land. Both polar regions became sources of cold "polar" air that contrasted strongly with the warm air from equatorial regions. The Pleistocene and Recent climates, characterized by marked zonality, were thus established. Growth of glaciers requiring for the most part only ample precipitation on cold continental regions (for example, Haurwitz, *44*) was greatly favored by this climate. The Pleistocene type of climate may thus be expected to continue as long as the poles remain near their present thermally isolated positions.

The motion of the poles was probably somewhat intermittent. If we consider convection to be the mechanism producing this motion, orogenies would be good indicators of convectional activity. The beginning of rapid polar motion would coincide with the major orogenies at the end of the Tertiary, and possibly also at the end of the Cretaceous. The climatic oscillations within the Pleistocene were far too rapid to be related to movements of the pole in and out of the Arctic region.

As a consequence of the theories proposed, the principal alternations between glacial and nonglacial stages would occur in the arctic. Relatively minor changes would be expected in the antarctic, resulting primarily from the slight warming and cooling of the Atlantic Ocean. Despite these minor changes, such as the present decrease in antarctic ice, the theory requires a secular increase from zero thickness at the beginning of the Pleistocene glacial epoch. There is some evidence that this has occurred. In many parts of the world, phases of high sea level are recorded by elevated beaches. Although there is some disagreement about correlations, many authors—for example, Zeuner (*43*)—identify five or six such beaches, at elevations up to about 100 meters. Zeuner showed that a graph of beach elevation against time is approximately linear. He recognized that "it seems probable that this straight line represents a more or less continuous drop of sea level in the course of the Pleistocene on which the oscillations due to glacial eustasy were superimposed." It is now suggested that this apparently secular decrease in sea level, with attendant preservation of the beaches showing successive decreasing sea level maxima, can be accounted for by the secular growth of an antarctic ice cap. Numerous estimates that the total decrease in sea level due to present ice caps is about 60 meters have been made; an additional decrease of about 50 meters can be attributed to thermal contraction of the sea water, if the present mean ocean temperature is taken as about 10°C below the Tertiary mean. We can thus provide for a secular decrease in sea level of about 100 meters, which seems to account for the highest of the elevated beaches.

Conclusions

The theories of the origin of the Pleistocene glacial climate and of the glacial and interglacial stages proposed here are in complete harmony with the doctrine of uniformitarianism. No external influences or catastrophic events are required to initiate or maintain these conditions. It is postulated that some mechanical process has caused the poles to migrate to positions very favorable for the development of glacial climates. The major changes within the Pleistocene are considered here to have resulted primarily from the alternations of ice-covered and ice-free states of the surface of the Arctic Ocean.

For the most part, this article pertains to the Pleistocene glacial epoch and the warm interval between the Permian and the Pleistocene. Although little is known about possible glacial and interglacial stages during the Permian and Proterozoic glacial intervals, the initiation of such intervals could have been a consequence of the same mechanism as that proposed here for the initiation of the Pleistocene. The "warm" periods prevailing during the long intervals between the times of glaciations before, as well as after, the Permian could also be explained, according to the theory proposed, as a consequence of the location of the poles in regions of freely circulating oceans.

The consequences of the ideas presented are that the Pleistocene climate will continue while the poles maintain their present locations and that the Recent epoch can be considered as another interglacial stage.

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Each science confines itself to a fragment of the evidence and weaves its theories in terms of notions suggested by that fragment. Such a procedure is necessary by reason of the limitations of human ability. But its danger should always be kept in mind. For example, the increasing departmentalization of universities during the last hundred years, however necessary for administrative purposes, tends to trivialize the mentality of the teaching profession.
—Alfred North Whitehead, *Nature and Life* (University of Chicago Press, 1934).