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Thermodynamics of an Ice Age: The Cause and Sequence of Glaciation

Gilbert N. Lewis
University of California, Berkeley

MANY OF THE OLDER THEORIES of an Ice Age assumed that glaciation was due to a general lowering of terrestrial temperatures—for example, by diminished solar radiation. It has, however, become evident that glacial periods have often been associated with intense precipitation in all parts of the world, leading to the formation of large lakes, some of which are now nearly or quite dry. Unless precipitation was local, it must have resulted from abnormally high evaporation; hardly reconcilable with lower temperatures.

Jeffreys (*4*) has pointed out in his critique of glaciation theory that the only sure correlation between glaciation and other known phenomena is that each great Ice Age has been ushered in by a period of unusual land and mountain formation.

This is not merely an empirical observation. It was made plausible by Ramsay (*6*) that great land elevation should produce conditions favorable to glaciation. Brooks (*1*) developed this idea further and even claimed that in one of the great Ice Ages the peculiar geography of the time was able to produce a widespread glaciation centering in the tropics.

Admitting that large and high land masses afford a predisposition toward glacier formation, we must still look for the cause of the individual advances and recessions of the glaciers during single Ice Ages, within the last of which, at least, no great, discontinuous, geographical changes are believed to have occurred.

A new and ingenious theory of Sir George Simpson (*7*) attributes an Ice Age to an *increase* in solar radiation. He believes that glaciations come in pairs, each pair being caused by a single rise and fall of solar radiation, as shown in his diagram, one of the identical halves of which is reproduced in Fig. 1. He assumes that the four main glaciations of the Pleistocene period were caused by two such periods of intensified solar radiation, one of which is shown in Curve I. The average temperature of the world is assumed to follow a similar course (Curve II). Curve III indicates the course of average annual precipitation, and Curve IV represents, according to Simpson's theory, the total amount of glacial ice, the two maxima representing one pair of the main glaciations.

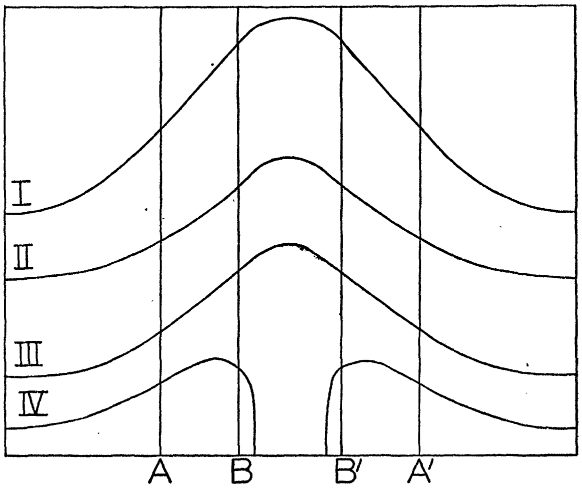

FIG. 1. Simpson's diagram: I—Solar radiation; II—Temperature; III—Precipitation; IV—Total ice.

In physics and chemistry, with the single exception of the phenomenon of momentum, there is no such thing as habit: a process is determined solely by present conditions. In meteorology the only momenta that need be considered are those of air and ocean currents, and since these momenta would be dissipated in a few weeks or months if their causes were removed, a criterion of the truth of any theory must be that the occurrences over a long period of years are due only to the conditions then prevailing. The above theory does not meet this criterion. According to the diagram, at A and A′ there are identical conditions of radiation, temperature, average precipitation, and total glaciation. If the glaciers are increas-

Dr. Lewis died 23 March 1946, shortly after submitting this, his last paper.

ing at one of these points, they must be increasing at the other. But this is not the state of things shown in the figure. Again, at B and B′, under identical conditions, the figure shows glaciers to be rapidly receding at the first point and rapidly advancing at the other. While we have not proved that an increase in solar radiation might not give rise to a glaciation, physical chemistry denies that the sequence of events can accord with Simpson's theory.

There are still adherents (*9*) of the astronomical theories of glaciation initiated by Croll (*3*), and there is no doubt that any change in the orbit of the earth or in the direction of the polar axis, as well as any change in solar radiation, must produce marked changes in our climate. Nevertheless, it remains doubtful whether any such changes have been of sufficient magnitude to produce a great glaciation. It seems more likely that the cause of glaciation is to be found in purely terrestrial happenings.

Any discussion of an Ice Age must deal with a whole complex of phenomena which includes not only the intense pluvial and glacial periods but also long periods of cool, dry climate, during which the great loess deposits were formed. These periods of drought were believed by Penck and Brückner (*5*) to begin before the peak of glaciation. This conclusion, which seems at first sight somewhat remarkable, we shall find in accord with physicochemical deductions.

Regarding the major glaciations, of which there have been four since the beginning of the Pleistocene period, it is evident that as long as polar icecaps exist there will always be fluctuations, increasing and decreasing the extent of glacial ice. However, each major glaciation was an event of such colossal magnitude, several per cent of all the water of the oceans being deposited upon the ice fields, that some sort of a runaway process is suggested. It seems that when a climatic fluctuation exceeds a certain magnitude, a condition of instability is reached in which some self-accelerating process makes glaciation proceed for some time without hindrance. We must now look for possible causes of such a phenomenon.

Two Self-accelerating Processes Conducive to Glaciation

Process A. One of the meteorological phenomena having great influence upon the formation of glaciers was mentioned by Croll (*3*) and has since been widely discussed. When sunlight falls upon land or sea, it is largely absorbed, but, when the surface is covered with ice and snow, the albedo (reflectivity) is much higher, reaching 0.80 for fresh snow or hoarfrost. On the other hand, such surfaces are nearly black bodies for the radiant energy of very long wave length, which almost alone constitutes the thermal radiation from the earth's surface. Thus, when land or ocean, without much change of temperature, becomes covered with ice and snow, energy is emitted at about the same rate as without such covering, but the energy received from the sun is only from one-half to one-fourth as much. The surface and the neighboring air become much colder, and, as this cold air spreads, more ice is formed in the neighborhood. Thus, every glacier tends to spread, such a spreading being limited only by circulation of air from warmer regions. This tendency of ice to produce more ice is illustrated by the fact that minor climatic changes produce major changes in the amount of ice in the Barents Sea (*8*).

With reference to Brooks' (*1*) idea that a great glaciation may have occurred in the tropics, we may inquire what would happen if the whole surface of the earth—land and water—were covered by ice and snow. Let us assume, as a hypothetical case, that the whole surface is covered with snow or rime with an albedo of 0.80, that momentarily it has a temperature just below the freezing point, and that the sky is free from clouds. Under these circumstances the rate of emission of thermal energy would greatly exceed the energy received from the sun. The temperature, even at the equator, would fall greatly. In making this calculation we have used numerical data occasionally from the work of Sverdrup, Johnson, and Fleming (*8*) but chiefly from Brunt's meteorology (*2*).

Under ordinary conditions of cloudiness and albedo, Q_A, the average solar radiation absorbed on a horizontal surface, at the equator, is 0.34 units (small cal./cm.^{2}/min.). The thermal emission, Q_E, averages 0.30 units. The difference, $Q_C = 0.04$, by processes of evaporation and air circulation, is carried to those parts of the earth in which the energy emitted exceeds the energy received from the sun. On the completely glaciated world as we have pictured it, the solar radiation at the surface would be much greater because of the lack of clouds. Without clouds, the amount of solar energy reaching one horizontal square centimeter at the equator (averaged through the year) is obtained by subtracting from the solar constant 9 per cent for reflection from the atmosphere and 5 per cent for absorption by ozone, and then integrating over all angles of incidence of the radiation. The result is 0.50 units. If the albedo is as high as 0.80, only 20 per cent of this radiation is absorbed, Q_A becoming 0.10.

The amount of heat radiated under these same circumstances is hard to estimate. Using Brunt's empirical equation for the effective surface radiation as a function of the humidity of the surface air, and taking the partial vapor pressure at the surface as the vapor pressure of ice at 0° C., we find that the effective radiation would be 0.34 times the radiation given by Stefan's law at 0° C., which makes Q_E, the average energy emitted from the surface, approximately 0.16. Since Brunt's equation admittedly does not give a reasonable extrapolation to zero humidity, it is evident that a good deal of the radiation from the atmosphere back to the earth must be due to moisture high in the atmosphere, where humidity measurements cannot readily be made. Under the conditions of complete glaciation this moisture content at high altitudes would also presumably be reduced, and the true loss by surface radiation would then be considerably greater than that just obtained—perhaps 0.24. However, even if the low value, 0.16, is used and energy lost by atmospheric circulation, ignored when this is compared with 0.10 for the heat received, it is apparent that there would be a great cooling, even at the equator.

However, old glacial ice often has an albedo much lower than that of snow. If an albedo is 0.60, Q_A would be 0.25. Whether such a surface would become colder, or would melt, depends upon the value taken for Q_E. If the albedo should drop to 0.50, or even lower, because of some deposit of volcanic dust, Q_A would certainly be greater than Q_E, and the glacial ice would melt. If this occurred over the ocean, even in a limited area, the water would tend to spread, for this would also be a self-accelerating process. It seems likely, therefore, that even a completely glaciated world would eventually return to normal conditions.

By itself the albedo process, pronounced as it is, seems inadequate to produce the runaway phenomenon of a great glaciation. If a glacier spreads, not only will the average temperature decrease, but the periphery will move nearer to the tropical regions. Thus, in two ways the average temperature change per degree of latitude will increase. It is upon this rate of change of temperature with the latitude that all atmospheric circulation basically depends. Therefore, when a glacier advances, there will be an increase in the general circulation of the atmosphere, and this will increase the amount of heat carried from lower to higher latitudes. This would seem to be a sufficient automatic method of preventing an indefinite expansion of the ice fields, were it not for another phenomenon that must now be considered.

Process B. This process is self-accelerating and not self-limiting, so that, when once started, it should go on increasingly until some other factor brings it to an end. The process has the effect of a specific sort of siphoning of water from the warm oceans to a glacier. In using such terms, however, we must not think of anything spectacular. It is the main thesis of this paper that the remarkable phenomenon of a great glaciation is due to slow, cumulative effects of small but continued departures from normal climatic conditions.

A large ice field is the source of an extended, nearly homogeneous, and very cold and dry air mass. As this moves and ultimately interacts with the warm and humid air of lower latitudes, it causes precipitation, some of which, falling at or near the periphery, will produce a temporary or permanent extension of the glacier. There will also be precipitation over the whole ice field. Even the most humid airs of the tropics retain 20 to 30 per cent of their moisture at 0° C., but most of this residual moisture can be precipitated, often as light snow or ice fog, over the interior of the ice fields, where far lower temperatures are attained.

The interaction of air masses as determined by continents, oceans, and the seasons is not our present concern. We must consider here average changes, not between summer and winter, but over centuries and millennia. The effect of glacial expansion must be to produce a more extended, more homogeneous, colder, and drier air mass. Thus, while an increasing percentage of total evaporated water will condense upon the ice field, the greater mass of drier air, as it moves away from its source, will diminish the average humidity of the whole atmosphere. This drier air over the warm oceans will cause an increased evaporation, which will also be aided by greater air velocities, if the increase of general atmospheric circulation that has been mentioned causes generally greater windiness. We thus have a greater precipitation on the ice fields, greater evaporation from the oceans, but less humidity and less precipitation throughout the rest of the world. This siphoning effect should increase as the glaciers advance, to be stopped only by some factor not yet considered.

Probable Immediate Cause of a Great Glaciation, and the Sequence of Glacial Events

The stage seems to be set for an Ice Age by unusual land and mountain formation, and under these favorable circumstances, as indicated above, there are two self-accelerating processes which may permit relatively minor climatic changes to produce a major glaciation. Because of the runaway character of such a glaciation we cannot decide with any certainty what sets off the event. However, there is one type of meteorological change that presumably initiated at least some of the major glacial advances and that certainly must produce such a result if the change is of considerable magnitude.

The extension of a glacier may be produced not only by a lowering of the local temperature but also by an increase in precipitation, and it would seem that a long-continued increase of precipitation over the glaciers, amounting to a few per cent, could produce a sufficient glacial growth to start the runaway process. Such an increased precipitation would result if the total net evaporation from the oceans were increased correspondingly. An examination of the rate of evaporation from the oceans in various parts of

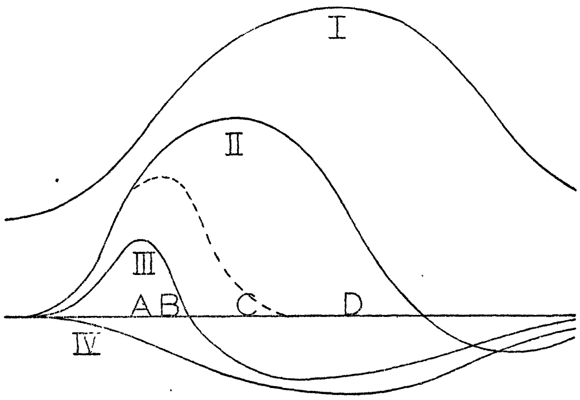

FIG. 2. Sequence of glacial events: I—Total ice; II—Evaporation; III—Precipitation, far from glacial area; IV—Temperature, far from glacial area.

the world (*8*) reveals that many small factors must be involved. Primarily, the evaporation at any point depends upon the surface temperature of the ocean and the dryness and velocity of the air. Only slight changes in these factors would cause a considerable change in the evaporation. For example, if the velocity and humidity of the air should remain constant, we can imagine a small upthrust at the bottom of an ocean to divert a warm current into a region of greater windiness or to spread the warm water over a larger surface. At present the region of greatest net evaporation per unit surface is the Atlantic on either side of the equator, where conditions would seem not unfavorable for such a change. By such an effect, or another, there are presumably fluctuations in the average evaporation and corresponding fluctuations in the precipitation upon the ice fields. When an increase in precipitation exceeds a certain value, we may assume that the runaway process may be initiated.

It is known that a great glaciation is no single event and that there are numerous advances and retreats, but for the sake of simplicity we shall ignore all of these fluctuations and attempt to find the general consequences of a period of high average evaporation. However, if a major glaciation consists of a number of phases, in each of which there is a great advance and retreat of the glaciers, it would seem that the following deductions would be approximately applicable to each phase separately.

Let us consider a time, something like our own climatically, in which there are fluctuations in evaporation, none of which, however, are great enough to have major consequences. Finally there comes a period of great evaporation, represented in Fig. 2 by the beginning of Curve II. It would, by itself, have a maximum at some point, B, and return to normal according to the dotted curve. However, at about A the runaway process begins, the course of evaporation following the full Curve II. The amount of glacial ice would then follow some such curve as I, and the temperature at some point far from the ice fields, such a curve as IV. As soon as the siphoning begins, precipitation at some point far from the ice fields (Curve III) begins to fall and soon becomes less than normal. The resulting long period of drought, beginning some time before maximum glaciation, continues until all conditions return gradually to normal. The reason for the cessation of the whole process must be that eventually the great loss of solar energy, due to the albedo effect, causes a general lowering of temperature that ultimately reaches the surface waters of the tropics (point C). Because of the great change in rate of evaporation with temperature, presumably these surface temperatures would need to be lowered only 1° or 2° C. in order to produce sufficient diminution in evaporation to bring the whole glacial epoch gradually to a close.

The schedule of events during a glacial epoch are more complicated when there are large fluctuations of advance and retreat of the ice. Local climatic events may also be governed by special conditions. Fig. 2 shows the probable sequence of events for the world as a whole. First comes the pluvial period, during which it is probable that wide glaciation occurs on the tropical mountains. On the other hand, it seems likely that the Alps, lying so close to the main glaciers, have a chronology approximating that of the Arctic icecap. The pluvial period is followed by a long period of cool and dry climate which precedes and continues through the peak of glaciation itself. Finally, the whole process wanes, the initial conditions being gradually restored.

It has not been proved that every major glaciation is preceded by a pluvial period. There may be some combination of other factors than evaporation that could start the siphoning process. In such a case the sequence would begin with a period of increasing drought, followed by the peak of glaciation. In either case physicochemical considerations lead to the same conclusion as that reached by Penck and Brückner—the peak of glaciation is preceded by a period of cool, dry climate and continues nearly to the end of glaciation. If there is a pluvial period, it must occur, not at the end, but near the beginning of the glaciation.

References

1. BROOKS, C. E. P. *Climate through the ages.* London: Ernest Benn, 1926.
2. BRUNT, DAVID. *Physical and dynamical meteorology.* Cambridge, Engl.: At the Univ. Press, 1939.
3. CROLL, J. *Climate and time.* London: Daldy, Isbister, and Co., 1875.
4. JEFFREYS, HAROLD. *The earth.* (2nd ed.) London: Cambridge Univ. Press, 1929.
5. PENCK, A., and BRÜCKNER, E. *Die Alpen in Eiszeitalter.* Leipzig: Tauchnitz, 1909.
6. RAMSAY, W. *Ofv. Finska Vet. Soc. Forh.*, 1910, **52**.
7. SIMPSON, SIR GEORGE. *Nature, Lond.*, 1938, **141**, 591.
8. SVERDRUP, H. U., JOHNSON, M. W., and FLEMING, R. H. *The oceans.* New York: Prentice-Hall, 1942.
9. ZEUNER, F. E. *The Pleistocene period in Europe.* London: Royal Society, 1945.

Association Affairs

West Point and the AAAS

Sidney Forman, *Archivist*
United States Military Academy, West Point, New York

A RECENTLY CATALOGUED GIFT to the United States Military Academy library discloses a heretofore unknown close relationship between West Point and the foundation of the AAAS. The gift consists of printed records published during the years 1830–32 by the American Association for the Promotion of Science, Literature, and the Arts.[1] This society, the records reveal, was formed on 16 May 1829 by a group of 24 cadets with the initial title of The Associate Society of West Point. Within a year it contained 88 members, including nearly all of the Academy professors and assistant professors. The membership published a grandiose plan to advance every phase of American culture and achieve a national organization similar to the French Institute or the Royal Society of London but more broadly and democratically conceived. They had in mind the general promotion of knowledge through associate organizations in every town and village in the United States and, in addition, suggested several projects which might be undertaken by the national society:

> They might advance the cause of education, by selecting the best books for general use, and by introducing a uniform and superior system of instruction. They might define and fix the pronunciation of our language, so as to secure a perfect uniformity therein, throughout the Union. They might promote our national literature by criticizing American publications and recommending valuable works to general patronage. They might extend the limits of science by new experiments and discoveries, and enrich the useful arts by important improvements and inventions. They might collect and diffuse much practical information and useful knowledge by periodical publications. Finally, they would unite the feelings and interests of all parts of our republic and thus cement more firmly that confederacy which has been the source of our civil, political, and religious freedom.

Soon after the formation of the first group at West Point and the election of a corresponding committee, an Associate Society of Schenectady was organized at Union College. This included 94 student and faculty members. A similar group was set up at the University of Nashville, Tennessee, and others at Utica, New York; Miami University, Oxford, Ohio; Rochester, New York; New York City; Jewett City, Connecticut; Gallatin, Tennessee; and Newport, Rhode Island.

There is no record of what happened to the society or its activities after 1832. The interesting connection with the AAAS is shown in the fact that many of the prime movers of the West Point group were among the charter members and founders of the Association.[2] One of the more distinguished examples was William W. Mather, who was assistant professor of chemistry, mineralogy, and geology at West Point from June 1829 to June 1835, during which time the West Point association flourished. He was one of those who in 1840 formed the original Association of American Geologists, which in 1847 resolved itself into the AAAS. Roswell C. Park, a leading spirit in forming the West Point society in his cadet days, became a charter member of the Association in 1848. It is an interesting note that Park asked the Association in 1849 to consider a plan of introducing uniform standard books for elementary and collegiate education, a

[1] The gift of Miss Mary Park, daughter of Roswell C. Park, included: *Exposition of the objects and views of the Associate Society of West Point.* New York: J. & J. Harper, 1830; *J. Amer. Ass. Prom. Sci., Lit., Arts,* 1831, **1**, Nos. 1–4 (2nd ed., rev. by the Central Committee); printed circular letter signed by Roswell Park, Newport, Rhode Island, 10 April 1832, 4 pp.

[2] See *Proc. Amer. Ass. Adv. Sci.,* September 1848, pp. 144–156.