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A Suggestion As to the Cause of Glaciation: The Reciprocal Reinforcement Theory[1]

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The Temperature of the Earth[2]

The temperature of the earth depends largely upon the energy received from the sun, and the promptness with which this energy is returned to space. In the long run the energy received by the earth must be equal to that given out. If the energy received is returned at once, it will have no effect upon the temperature of the earth. In this case the earth will be just as cold as it would be if the sun did not exist. This means, of course, that there must be a lag in the return of solar energy if it is to heat the earth. The earth either reflects or absorbs the energy it receives. If it is reflected, it is returned to space without lag and hence has no effect. If it is absorbed, its return is delayed and it becomes effective.

There are two ways of expressing the temperature of the earth. It may be expressed as its effective temperature as an astronomical body. If the earth could be observed from far out in space, its temperature could be approximately determined by Stefan's law of black body radiation. The result obtained by this method would not necessarily

[1]Below are the names of those who read and criticized the manuscript of this paper. Some of the criticisms were favorable, some unfavorable. All were helpful: John D. Boon, Jr., North Texas Agricultural College; Claude C. Albritton, Jr., U. S. Geological Survey; Frank C. McDonald, Southern Methodist University; Howard A. Meyerhoff, Smith College; F. R. Moulton, Secretary A.A.A.S., Washington, D. C.; Ellis W. Shuler, Southern Methodist University; A. C. Trowbridge, University of Iowa; C. C. Wylie, University of Iowa; William H. Hobbs, University of Michigan.

[2]The small amount of heat coming from the interior of the earth is neglected in this paper.

be the temperature at the surface or any other particular level. It would be the integrated measurement of the temperature at all levels that are sending radiant energy out into space. This value is not important in this paper. The other method of expressing the temperature is to give its value at the bottom of the atmosphere, or at what we call the surface of the earth. It is at this level that glaciers are formed, hence when temperatures are mentioned in this paper they refer to this surface.

What determines the surface temperature of the earth? The answer to this question involves three primary factors. First, the amount of radiant energy that penetrates the atmosphere and reaches the surface of the earth. Since the atmosphere is transparent for the major part of solar energy, and since this has been true, in all probability, for a long period of time, it will receive no further consideration. The second factor that controls the surface temperature of the earth is the coefficient of absorption of the materials that are found at the surface. Three different materials make up the major part of the earth's surface. They are water, soil, and snow. Trewartha[3] gives the coefficient of absorption of soil as 85 to 90 percent. Water has about the same coefficient. Petterssen[4] gives the coefficient of snow as 20 per cent. Some tables give snow a value as low as 7 per cent[5].

The varied coefficients of absorption of the principal surface materials indicate clearly that if their relative areas should be changed to a considerable extent, the temperature, locally, would be changed. An earth covered with snow would be cold not primarily because snow is cold, but rather because snow is a poor absorber of radiant energy.

The third factor involved in the temperature of the earth is the opacity of the atmosphere for solar and earth radiations. It happens that this blanket is more trans-

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[3]Trewartha, G. T., *An Introduction to Weather and Climate*, 1937, p. 21. (McGraw-Hill Co.)

[4]Petterssen, S., *Introduction to Meteorology*, 1941, p. 74. (McGraw-Hill Co.)

[5]Hodgman, C. D., and H. N. Holmes, *Handbook of Chemistry and Physics*, 25th Edition, 1941, p. 2119. (Chemical Rubber Co.)

parent for solar radiations coming in, than for earth radiations going out. There are three constituents of the atmosphere that account, largely, for its opacity for earth radiations. They are carbon dioxide, ozone, and water vapor. The first of these, carbon dioxide, may have changed rather largely during geological time. There is no proof of this, however. Ozone may also be subject to change. Water vapor varies widely from day to day and from point to point. These are the factors that control the temperature of the earth.

Reciprocal Reinforcement[6]

If two factors, *a* and *b* are so related that a change in *a* produces a like change in *b*, and in return the change in *b* produces a like change in *a*, etc., so that in this way *a* and *b* build up together until they reach their maximum values, this may be termed Reciprocal Reinforcement. There are many illustrations of this principle in science. The physicists makes use of it to build up the magnetic field and current in a series-wound dynamo. It is also used to build up the oscillations in a radio broadcasting tube. It is probable that it operates far more frequently than we realize, and that this is true in particular of climate and weather.

Why Are the Polar Regions Cold?

First, because the total annual insolation is small. This is due, of course, to the obliquity of the sunshine, and the fact that for a large part of the year the sun does not shine at all. Second, because the polar regions are either partly or completely covered with snow, nature's best reflector, throughout the year. The Antarctic glacier covers an area of about 5,000,000 square miles, and this surface is frequently renewed by the fall of fresh snow. If the sun should cease to shine on this surface, the pole would be little colder than it is. The area of the Arctic that is glaciated is much smaller than the Antarctic.

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[6]The principle of reciprocal reinforcement has long been recognized. The name "reciprocal reinforcement" may be new; it was suggested to me by Richard Maxwell, a student of physics at Southern Methodist University.

The Ice Invasion[7]

The Antarctic Ice Cap is as large as the land area will permit; it covers all of the land excepting a few high points. The coverage in Greenland is not complete since there are many bodies of land along the margin of the continent that are not glaciated. All of these, with one possible exception, have been covered with glacial ice in times past. These unglaciated bodies of land are not, necessarily, evidences that the glacier is retreating. Whether or not a body of land is completely covered with ice is a matter of its size as well as its location. Few, if any, small islands are completely glaciated, no matter how favorably they may be located. There is a very definite reason why this is true. The ratio of the marginal area to the area of the interior feeding-ground is a determining factor. In small islands the area of their margins is large as compared with the area of the interior. Antarctica is about six times as large as Greenland, while the area of a strip, say fifty miles wide, around the margin of Antarctica is a little more than twice the area of a strip of the same width around the margin of Greenland[8]. If Greenland is shrinking, the interior area must be decreasing more rapidly than the area of its margin, and this means that it is becoming increasingly more difficult for the ice sheet to cover the margin. In the long run there must be a complete adjustment between the available ice from within and the coverage at the margin. This adjustment may now be going on with the ice sheet in what appears to be a retreat. The retreat of mountain glaciers in recent geological times may be due to the removal of the nearby continental glaciers and their cooling influence. The retreat of glaciers is not a proof that the earth, as a whole, is now passing from a cold to a warm period.

If either Greenland or Antarctica should become larger, it is probable that the ice sheets would become larger. This

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[7]The theory that the Pleistocene glaciers were not formed *in situ* has been advanced before. See Flint, Richard Foster, "Progress and Problems in the North American Pleistocene," *Journal of Geology*, v. 50, p. 576, August-September, 1942.

[8]These figures are not exact, but they are of the right order.

contention is well supported by the fact that from both of these continents the ice is slipping off of the land into the ocean to form icebergs. Just how long the enlarging ice sheets would be able to keep pace with the enlarging land surface, it would be difficult to say. If Antarctica should become sufficiently large, the glaciers might extend as far northward as the Greenland glacier extends southward. If this should take place in all directions, the area covered would be approximately 13,000,000 square miles. Who can say that it would stop here? How greatly would the temperature, locally, be affected by the reduced absorption that would take place over this vast area?

It would require a great expansion of the Antarctic Ice Cap to make it possible for it to reach a continent of the temperate zone, for the simple reason that there are no continents near by (a condition that may not have prevailed during the Permian Period[9]). However, in the case of Greenland all that is needed to bring about an invasion is a land bridge across Baffin Bay. If this bridge should be formed, the invasion, aided by reciprocal reinforcement, could begin. As the ice sheet expanded, the area that would reject, by reflection, solar energy would be enlarged, thus lowering the temperature and aiding in the expansion of the ice sheet. Thus invasion would aid invasion. Reciprocal reinforcement would be aided by other factors. The reduction in temperature would reduce the capacity of the air for moisture and in this way impair its blanketing effect, while the increased elevation due to the thickening ice would also lower the temperature[10]. All of these factors are real and they all join in reciprocal reinforcement.

The Retreat of the Ice Sheet

It may be said that if all of these factors act in reinforcing each other, glaciation would proceed until all lands were covered. This is not true. All reciprocal actions come

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[9]See, *A Textbook of Geology;* Pirsson and Schuchert, 1915, 759. (John Wiley and Sons.)

[10]This reciprocal factor was suggested by Howard A. Meyerhoff, Smith College, Northampton, Mass.

to an end. In this case the most powerful factor in producing the low temperature is the immediate return of solar energy by the reflection of freshly fallen snow. This power is in time lost to a large extend by the merging of the snow crystals into solid ice, ice that is often mixed with earthy matter such as dust and moraine. In the polar regions where snow falls frequently in both summer and winter, the power to reflect solar energy is continually renewed. This is not true of regions far to the southward. Glaciers that move far enough into warm climates will lose to a great extent their power to reflect radiant energy, and this combined with the increasing insolation, puts a limit on the invasion.

If perchance the bridge that made possible the invasion should be destroyed by submergence, the parental source of the ice would be cut off by a broad strip of water; and since water is a good absorber of solar energy, the invasion would not only cease, the southern end of the glacier would be forced to melt. If after the destruction of the bridge there were no large land masses left in the arctic zone, the glacier might disappear completely.

Is This Theory Adequate?

The Pleistocene ice sheet, at its maximum, covered about 4,000,000 square miles in North America. The area in Europe and Asia was not quite so large. In addition to this it is probable that the ice covered a large area that is now below the sea. Taking these facts into consideration, it is reasonable to assume that no less than 8,000,000 square miles of the earth's surface that now absorb 80% of the solar energy that falls upon it, absorbed only 20% during the glacial stages of the Pleistocene. The 80% and 20% represent the coefficient of absorption of soil and snow, respectively. Falling from 80% to 20% is a reduction of 75% over the area of 8,000,000 square miles, or a fall of about 3% for the entire earth, since the area of the surface of the earth is about 200,000,000 square miles.

A loss of 3% in the energy absorbed by the earth would have little effect upon its temperature if the loss were sustained by the whole 200,000,000 square miles. Calculation indicates that it would not lower the temperature by more than one or two degrees centigrade. However, the loss would not be sustained by the earth as a whole, but largely by the 8,000,000 square miles that failed to absorb the normal amount of energy. If heat were readily transmitted over the earth, the temperature would be the same everywhere. But the fact is that the transmission of heat is totally inadequate to bring about an even distribution. A region that absorbs but little solar energy will be cold and one that absorbs a large amount will be warm. The varied climates of the earth, with temperatures that differ by 180°F, is proof that heat is not evenly distributed. For these reasons the deficient supply of a glaciated region is borne by the surface that fails to absorb it. This means that a glacier must reduce the temperature, locally, to a great extent and this is true no matter what other factors may have had a part in bringing about glaciation. Glaciers bring their own cold weather as they come. It is possible that during the Permian, ice sheets were so large that they affected to an appreciable extent the temperature of the earth as a whole.

The Birth of a Glacier

In spite of the fact that glaciers have occurred rather often, many geologists believe that the earth has been fairly warm and moist from pole to pole during a large part of geologic time. Why then have glaciers come upon a warm earth? Is it the sun, the atmosphere, or the nature of the surface materials that are at fault? The answer to this question, according to the theory suggested in this paper, is that the primary factor in bringing these changes has been the variation in the power of absorption of the surface materials operating in conjunction with the principle of reciprocal reinforcement. Glaciers come when there are large bodies of land within the polar circles that extend into the temperate zones, and when these lands are so situated that precipitation exceeds melting and sublimation.

Glaciers are not necessarily the coldest spots on the earth. Polar lands are sometimes colder than polar seas or polar glaciers. One of the cold regions on the earth is the northern part of Siberia. Here, during the winter season, the land is colder than the ocean to the north. It is not difficult to explain this low temperature. Heat is transferred over the earth by convection only. On the land there is but one system of convection currents, the winds. The sea has two systems of convection currents, the winds and the water currents. This means that the sea is a better distributor of heat than the land. The vast snow-fields that cover Siberia during the winter reflect the solar energy, while the water to the north absorbs a large portion of it. This, combined with the fact that water has a much higher specific heat that land, causes the land to be the colder. Siberia would be glaciated today if the precipitation were sufficient.

Perhaps there was a time when the earth was warm from pole to pole; when the sea, the great absorber, the great storehouse, the great transmitter of solar energy was functioning at its best; a time when the effiiciency of the warm, damp atmospheric blanket was most effective; a time when there were no large bodies of land within the arctic circles to interfere with the distribution of heat; a time when there were no snow-fields to reject, by reflection, the energy of the sun.

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Far to the north a body of land began to rise above the water. As it grew it drove the sea southward, the sea with its power to store and transmit solar energy; it replaced the waters with a medium that had but little power to hold the summer heat. In time this land grew to be a continent; a continent that became progressively colder during the long half-year winter nights. Perhaps in time the temperature dropped to the freezing point of water, and snows began to fall; snows that reflected the energy of the sun and thus aided in their own formation, snows that remained over from season to season to form glaciers. Perhaps these glaciers inaugurated a new reciprocal factor, the anticyclonic down-draft winds that form over all glaciers and tend to enlarge the area that they cover. It is possible that a great glacial period came from these small beginnings[12].

Is this true? The sun burns on at a fairly uniform rate; the distance that lies between the earth and the sun is almost constant; the atmosphere suffers but little change in its composition. But the relative positions and areas of land and sea are subject to great changes, and many of the important geological events are brought about by these changes. Glaciation may be one of these events, for the things of the land are so different from the things of the sea.

[12]For an excellent description of these anticyclonic winds see: *The Glacial Anticyclone and the Continental Glaciers of North America*, 1943, by William Herbert Hobbs: (*The American Philosophical Society*.)