THE EVOLUTION OF CLIMATES

—BY—

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(Illustrated with Maps and Plates.)

I.

The Objects of This Paper.

The objects of this paper are to investigate and interpret the phenomena and principles of the evolution of climates. The most important of these relate to the present and near future, but the great questions involved cannot be fully considered unless the whole range of the phenomena of climate and the principles involved in its changes be taken up in their entirety.

As at present treated, the phenomena of climate belong to two branches of science—Geology and Physical Geography. The former takes up the phenomena and causes of the climates including and antedating the Ice age; the latter, through climatology and meteorology, deals with the present distribution of, and variations in, temperature, precipitation, atmosphere, pressure and winds.

Under this division of the subject, geological climates are dealt with as being separate and apart from the phenomena with which climatology and meteorology have to deal. These later branches of science, therefore, treat the phenomena and principles of existing climates as relating entirely to the present and near future, and regard these climates as practically constant over long periods of time.*

*Am. Jour. of Science—Vol. XLIII. p. 364.

This separation is a natural one, for the distribution of temperatures, during geological climates, appears to have been so different from that which now obtains that their allotment to different branches of science appears to be justified. But the conditions of geological climates merged so gradually into those at present existing, that a transition epoch of considerable length must lie between these two great eras. The two sciences of geology and physical geography, therefore overlap mutual fields of investigation in the climatic problems of this transition epoch. The principal of these problems are contained in the questions: What was the cause of the Ice age? and what are the principles which caused the Ice age to be replaced by existing conditions? Beyond the immediate sphere of these initial problems are others relating to past and future conditions.

An endeavor is made in this paper to interpret the secular changes of climate which mark geologic and present time in a logical and coherent manner, and to investigate especially the phenomena and principles of the period during which the transition from the climates of geologic time into those at present existing, took place.

II.

Earlier Views as to Climatic Control.

Prior to and including the first third of the last century, it was generally assumed and believed that the control of climates by solar energy had prevailed throughout the greater portion, if not all, of geologic time. The general conception of secular climatic variations was therefore simple. There had apparently been a period of torrid heat in all latitudes, controlled as at present by solar energy, which period was followed by milder and milder temperatures, due to the waning of this energy, until present conditions had been established. Based on the continued waning of solar heat, the reduction of temperatures below that degree necessary for life, was predicated, and the earth was thus regarded as passing into a condition of refrigeration and decrepitude.

These interpretations and beliefs were somewhat shaken in 1837, when Prof. Louis Agassiz announced his conviction that an age had been passed through during which land areas in the north temperate zone had been buried beneath continental ice floods, hundreds if not thousands of feet thick.

Upon the acceptance of the general interpretation of Agassiz, and after careful studies of the characteristics of ice action, it has been found that ice as a geologic agent has recorded its periodical existence during nearly all of the great divisions of geologic time.* These evidences of earlier ice action have especially been found in and adjacent to equatorial regions. The ice causing them existed during periods throughout which temperate and tropical life flourished in high latitudes.

The acceptance of these phenomena of ice action, as proofs of ice ages or glacial epochs, has entirely overthrown the first simple conceptions of climatic changes, and has substituted a very complicated series of "changes from cold to warmth and back again to cold." To account for these complications, and for the great extension of ice in post-Tertiary time, a number of theories have been advanced.

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*R. D. Oldham, Geol. Mag. (N. S.) Decade III, Vol. 3, p. 293-308.
C. D. White: Am. Geologist, Vol. 3, p. 299, et seq.

(NOTE) In the interpretations of the distributions and included strata of glacial drift, there have been introduced minor complications. These appear to be justified by the finding of certain evidences of cessation or recession of glacial floods to such an extent as to permit hardy types of life to supervene before another advance. These phenomena have given rise to the term *inter-glacial period.* Thus, within one of the great complications of climate are introduced minor complications, the causes and phenomena of which have not yet passed the debatable stage. Whilst throwing some light on glacial phenomena they cannot be fully considered until the causes of the Ice age and its disappearance shall have been more fully agreed upon.

In many, if not all of these theories, the evidences of early ice action in and adjacent to the tropics have been accepted as proofs of recurring ice ages, and it has been assumed that solar energy has controlled the climatic variations of geologic time.

Before essaying the task before us, it is considered necessary to briefly recall the principal of these theories and then to review the range of phenomena for which an explanation is sought.

(*a*) *Review of the Principal Theories which have been advanced to account for Glacial Epochs.*

(*b*) *Calculations of the duration of earth heat.*

(a) The theories which have been put forward to explain the phenomena of climate, and particularly those of glacial epochs, have been frequently and fully discussed.*

It will only be necessary, therefore, to briefly refer to the principal of these theories, which are as follows:

(1) A decrease in the original heat of the globe.

(2) Changes in the elevation of land, and consequent variations in the distribution of land and water and in climate.

(3) Changes in the obliquity of the axis of the earth.

(4) A period of greater moisture in the atmosphere.

(5) A coincidence of an aphelion winter with a period of maximum eccentricity of the earth's orbit (Croll).

(6) A combination of (2) and (5) (Wallace).

(7) Variations in the atmospheric content of carbon dioxide (CO_2) (Hogbom, Arrhenius, and Chamberlin).

**S. V. Wood, Jr.*, The Climate controversy. Geol. Mag. 1876 and 1883: *Dr. Jas. Croll*, Climate and Time, Climate and Cosmology: *Dr. Alfred Russell Wallace*, Island Life: Phil. Mag. May, 1864: Report Brit Assn. 1876: Proc. Royal Soc. Vol. XXVIII, p. 15: Quart. Jour. Geol. Soc., February, 1878, Nature, July 4th, 1878. Trans. Geol. Soc. Glasgow, Feb. 22, 1877. *Dr. G. Frederick Wright and Prof. Warren Upham*, The Ice Age in North America. *J. W. Gray, F. R. S. and Percy F. Kendall, F. R. S.*, Report Brit. Assn. 1892, p. 708. *Dr. Sir Robert Ball*, The cause of an Ice Age. *Prof. Geikie*, The Great Ice Age, edition of 1894, Chap. XLIII: *Luigi De Marchi*, (as quoted by Arrhenius), Phil. Mag. (5), Vol. 41 (1896), pp. 273-4.

Of these theories, those numbered from (1) to (6) inclusive have been investigated and found unsatisfactory by the leading students of this subject.*

The concensus of opinion of those competent to pass judgment upon the theories offered to explain the great secular variations in climate is, that no satisfactory nor acceptable explanation has been offered. This is true, not only as regards the problems of climate as a whole, but also as to the occurrence and disappearance of the Ice age, the change of temperature distribution from non-zonal to the present zonal, and the progressive rise in temperatures in middle and low latitudes since the culmination of the Ice age.

Not only have these theories separately failed to satisfactorily account for climatic changes, but no combination of them appears to prove any more acceptable. We therefore find ourselves confronting an unsolved problem, the scope of which is geologic time and which is declared by Croll to be "the most important problem in terrestrial physics."†

**Whitney*: The climatic changes of later Geological times, especially refers to (1).

Le Conte: Elements of Geol. (Ed. of 1891), p. 381 slightly favors (5) and (6).

Shaler & Davis: Glaciers, p. 70—especially abandons (1).

Becker: Am. Jour. Science, Vol. XLVIII (1894), pp. 106-7, discusses and dissents from (5)—(Croll).

Geikie: The Great Ice Age, (3rd Ed.) p. 816, admits that the problem is yet unsolved.

Bonney: Ice Work, Present and Past, p. 260. The problem of climate not yet satisfactorily solved.

De Marchi: (As quoted by Arrhenius) Phil. Mag. N. S. Vol. 41 (5) p. 273-4, all hypotheses must be rejected.

S. V. Wood, Jr.: Geol. Mag., Vol. 3, N. S. pp. 450-451—Rejects all, except variations in solar heat.

In addition to these, there have been advanced, (a) Variations in the amount of solar energy: (b) Variations in the heat absorbing power of the solar atmosphere: (c) Variations in the temperature of space. These hypotheses rest upon insufficient data for discussion.

†Climate and Cosmology, p. 1.

The Carbon Dioxide Theory:

Since the expression of the opinions just cited as to the insufficiency of the causes assigned by various authorities, as competent to produce an Ice age, a very elaborate theory has been put forward by Prof. Svante Arrhenius.*

This theory is based upon (1) The trapping power of carbon-dioxide upon the heat rays emitted by the earth, and (2) the sufficiency of variations in the atmospheric content thereof, to cause corresponding variations in its power to trap heat produced by solar energy; these variations giving warm and equable climates during periods of maximum, and cold climates during periods of minimum, amounts of atmospheric carbon-dioxide.

The causes of variations in the atmospheric content of this constituent are postulated upon slight variations in the results of the various modes by which it is supplied to the atmosphere from the rocks and oceans and in part restored thereto. These modes are very concisely and accurately stated by Hogbom, whose views are translated and quoted by Arrhenius.†

The calculations as to the effects of these variations are based upon the determinations by Langley, and other physicists, of the heat-trapping power of the atmosphere, and particularly of the carbon-dioxide content.

There can be no question as to the general accuracy of the determinations upon which the deductions of Arrhenius are based, nor of the present action of the water vapor and carbon-dioxide contents of the atmosphere in trapping those rays which the earth emits. He has, however, followed the now almost universally accepted assumption, that solar energy controlled the climates of glacial and preglacial ages; and has applied these principles without sufficient regard to the effect of the warmer oceans and the

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*On the influence of Carbonic Acid in the air upon the temperature of the ground. Phil. Mag. (5) 41, pp. 237-276. (1896).

†See pp. 269-273 of work cited. Similar views have been expanded in detail by Chamberlin, in the Journal of Geology, Vol. V, pp. 653-683 (1897) and Vol. VII, pp. 544-584; 667-685; and 751-787. (1899).

highly moist climates of those ages, and the resultant greater nebulosity of the upper regions of the atmosphere. He introduces into his calculations, it is true, corrections for present cloud distribution,* but none for the more general prevalence of cloud formations incident to the universally warmer oceans and moister air, which fossil life proves to have been the conditions existing during preglacial ages.

The universally warmer oceans of Tertiary and previous periods, must have interposed far denser and more extended cloud formations than those discussed in this theory. The conditions imposed were thus very different from those now prevailing, and the corrections for cloudiness should be correspondingly increased. When these conditions are met it will be found that the denser and more extended cloud-formation incident to the warmer oceans of those ages, would intercept solar energy in the upper atmosphere, and effectively prevent it from reaching the planetary surface to be degraded to that form of energy which the atmosphere traps. In the presence of a dense cloud-formation, the activity of carbon-dioxide as a heat-trapping agent would be restricted to the heat rays emanating from the planetary mass. It could thus have been one of the agents in the retention of whatever heat radiated from the surface, but not in the retention of converted solar energy, which, by the conditions imposed, must have been restricted in its effective action to the upper cloud surface.

Arrhenius does not show that the rise in temperatures which has manifestly taken place in temperate and tropical latitudes since the culmination of the Ice age, has been caused by a gradual increase in carbon-dioxide. If this rise is to be attributed to the cause assigned by this theory, it must be shown that an increase in the atmospheric content of carbon-dioxide competent to produce this rise has taken place. Moreover, that its distribution and effect have been such as to cause the non-zonal climates of Quaternary and Tertiary times to change into the zonal distribution of to-day. For why, if carbon-dioxide be the controlling factor,

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*See page 258 of work cited.

should the universally mild sea level climates prevalent anterior to the Ice age, be replaced by a zonal distribution of climates over which the atmospheric content of carbon-dioxide must be distributed quite as uniformly as when the non-zonal temperatures prevailed?

The same climate existed about lat. 30° during the Tertiary period as now exists in those latitudes, and during that period the same warm temperate climate was universal at all latitudes at sea level; whilst at present, there exists an extreme range from torrid to glacial.

If the content of carbon-dioxide were the controlling factor, this content must have been the same during the Tertiary period as it now is, to have produced the same general sea level temperatures about the latitude of the tropics; but during Tertiary times the sea level temperatures were uniform from one polar circle to the other, whilst at present every gradation of climate exists in this range from glacial to torrid, and glacial again, and only about the latitude of the tropics do temperatures prevail corresponding to those of the Tertiary period. It follows, therefore, that some other factor or factors than variations in the atmospheric content of CO_2 have caused the non-zonal temperature distribution of the Tertiary period to change to the zonal distribution of today.

To explain this change in the distribution of temperatures, upon the basis of variations in atmospheric carbon-dioxide, would necessitate an adjustment in the distribution of this content in exactly those proportions which would equalize the distribution of solar energy so as to produce the uniform effects at sea level from one polar circle to the other which characterized early Quaternary and late Tertiary periods. Such variations in distribution could not occur under the conditions of atmospheric circulation which now prevail, nor under any which could prevail in an atmosphere generally similar to that now existing. Besides, there remains the difficulty of explaining the absence of clouds during eras when the oceans were warm at all latitudes—as the life of those eras indicates a highly moist air. Nor is there evidence to justify the conclusion that the oceans have fluctuated in temperature during geologic time. The change in temperatures in them as recorded by fossil and existing life, is one continuous and gradual lowering from torrid to glacial, and then a rise in low and middle latitudes, with no change of moment in high latitudes.

Whilst denying that it has been shown that variations or fluctuations in atmospheric carbon-dioxide are competent to explain the differences between present climates and those recorded by fossil life and the phenomena of the Ice age, the writer, nevertheless, admits the importance of this agent as adding to the heat-trapping power of the atmosphere, and that it performed certain minor, but important functions, under the conditions which prevailed during preglacial ages; and furthermore, that it is also performing similar functions during the present era. But that it was, or is the controlling factor in climatic evolution, has not been shown nor made probable. Moreover, the author regards Arrhenius' magnificent contribution to the subject as an important step towards explaining one of the modes by which the earth heat, however derived, was conserved; and also, how since its exhaustion, the mean temperatures of middle and low latitudes have been caused to rise by the trapping of the heat derived from solar energy. This theory, furthermore, enables us to understand the character and significance of the processes now active, and which are yet producing important changes in climate. Arrhenius' work adds so much to the subject that it will be necessary to revert to his views in that portion of this paper dealing with those theories which have a definite bearing upon the problem as treated by the present writer.

From this review of the principal theories which have been put forward to account for the Ice age—the first of the important problems of climatic evolution— and from the expressions of the opinions of the highest authorities thereon, it is seen:—(1) That there is no agreement whatever as to the causes of geologic climate; (2) that there have been failures, not only in the attempts made to account for the Ice age, but also in those made to account for the change from the conditions then prevailing, into those at present existing. These failures must be the result of one or more of the following reasons: (1) Some premise, logically necessary, has been omitted; (2) some correctly grounded premise has been erroneously applied; (3) erroneous premise or premises have been admitted.

It will, therefore, be necessary to attack the problem on elementary lines, avoiding suppositions and assumptions, as far as possible.

(*b*) *Mathematical Calculations of the Duration of Earth Heat as a Factor in Climates.*

It will be noted, that in nearly all of the theories and discussions of climatic variation, the subject is treated from the standpoint of solar climatic control. The basis of this view is two-fold; 1st, it is natural to assume and accept as a fact that since climates are now under the domination of solar energy, they have been under such domination during all, or at least the greater portion, of geologic time; 2nd, certain high authorities tend to establish this assumption by endeavoring to demonstrate mathematically that the only other source of heat, namely, planetary or earth heat, could not have been an effective agent after the formation of a comparatively thin crust; and that the amount of this heat available for climatic influences was limited to that which could reach the surface by conduction, and that this crust was the principal, if not the only medium checking the loss of the available planetary supply by radiation into space.

In these calculations it is also apparently accepted that in the process of cooling, there was formed a primitive crust having about the same conductivity as granitic or basaltic rocks, and that planetary heat reaching the surface by conduction or other processes was exhausted by radiation into space. Notable among these calculations stands that of Sir William Thomson (Lord Kelvin).* The conclusions reach-

*Mathematical and Physical Papers, Vol. III, pp. 295-311, (Cambridge Ed. 1890).

ed in this, and such of the other calculations as the writer has been able to consult are, that owing to the low conductivity of rocks, earth heat could not have sensibly affected surface temperatures after the formation of a comparatively thin shell or crust, and therefore that such influence was restricted to the comparatively short period necessary for the formation of such a crust.

Reasons for Doubting these Conclusions.

(1) It is by no means certain that planetary, or earth heat which reached the surface by any mode whatever, was dissipated by direct radiation into space. There are now in operation very active conservative functions which may have been even more potent in the early geologic eras. These functions—moist air, clouds and carbon-dioxide—tend to hold heat, not in, but near the surface and to prevent its loss by radiation. These conservative factors are particularly effective in the case of dull heat rays such as the planetary surface emits:

(2) In the building-up of the strata known to the geologist and which have an aggregate thickness of twenty or more miles, there must have been worn away an equivalent thickness of the primitive crust. In this process, whatever planetary or mechanical heat this crust held or developed, must have been gradually liberated and brought into effect to warm the air and water and thereby influence surface temperatures. Estimates have been made aggregating many millions of years as the time necessary for the building up of known strata, during which time the heat liberated by denudation of the primitive crust or set free by other processes, must have been available for warming the water and air through which it had to pass before being finally dissipated into space, subject to all the conservative influences elsewhere pointed out. Therefore, it is not the amount of heat held in the comparatively thin crust, from which it could escape by conductivity, that must be dealt with; it is the far greater amount held in the materials of which the entire mass of rocks including and above the

Cambrian that must be dealt with. The heat held in these materials was liberated by denudation, a more effective process than conductivity, even though the crust had the conductivity of beaten silver:

(3) In addition, another factor, of greater magnitude than that which enters these calculations must be considered; namely, the heat held in the warm oceans of Archean and pre-Archean time:

(4) Included water, which is found in all deep-seated rocks, materially increases their conductivity; and deep-seated heat is brought into effective service by the circulation of meteoric water. Both of these processes may have been active upon the rocks of the earliest geologic eras, and either may have been of greater effect than conductivity:

(5) To these sources must be added the conservative action of solar and stellar energy for the entire period during which earth heat may have been a sensible factor in climatic control; for during the prevalence of the dual source, earth heat, by whatever processes it may have been developed, utilized and conserved, was farther conserved by heat developed by the absorption of energy radiated from exterior sources.

In the calculations above referred to, these factors are not considered; all of them are large in comparison with the heat which could reach the surface by conductivity, and some of them are of far greater moment in the problem under consideration—namely, the probable duration of earth heat as a sensible factor in the surface temperature of the earth during geologic time.

It is therefore held that calculations of the duration of earth heat as a climatic factor, based principally upon the conductivity of rocks, are misleading, by reason of the omission of the following important factors:

(1) The conservative action of the atmosphere and water in its various forms:

(2) The heat liberated by denudations, etc., and resident in the primitive oceans:

(3) The conservative action of active exterior sources of radiant energy.

Furthermore, it is doubtful whether the necessary data are available in that form which mathematical formulæ require, when in place of these data, hypothetical or assumed functions are substituted, the results, although mathematically accurate, may belong to a far different problem from the one attempted.

The present writer cannot, therefore, accept the results of the calculations of the duration of earth heat as conclusive, nor as establishing even in part the assumption that solar energy has been the dominant source of climatic control for the greater portion of geologic time.

III.

EPITOME OF PAST CLIMATIC CONDITIONS.

THE ICE AGE. *Extent of the evidence establishing its existence. Retreat of glacial conditions,—significance of this phenomenon. Tropical Glaciation,—disagreements as to its extent, and some authorities on both sides.*

The Temperate Age, The Tropical and Torrid Ages.

In order to have before us a comprehensive view of the phenomena which are to be accounted for, it may be well to review them as briefly as possible. This review can best be made backward from the present era, to the conditions generally admitted to have existed at the dawn of geologic time.

The record left by the last of the series of climates through which the earth has passed is the evidence upon which geologists have established the existence of the Ice age over the polar regions, the greater portion of temperate latitudes, and probably extending into tropical latitudes at sea level. It is certain that during the Ice age the snow line within the tropics descended much lower than at present, but the data upon which to study the extent of glacial conditions in these regions are yet very meager.

From the strata of each period, evidence has been found of ice action.* This evidence is so widely distributed and has been identified with such a degree of certainty, in some instances, that it must be accepted and accounted for by any one who attempts the great problems of the evolution of climates. Whatever may be the doubt or obscurity attaching to some of these evidences of ice action, it must be admitted that during each era from the Palaeozoic to the present, glacial ice has formed and has recorded and is yet recording its existence in a legible and characteristic manner, and this positive evidence cannot be omitted nor ignored.

Existing Glaciers—Their Relation to the Problem.

Wherever within tropical or temperate areas glaciers yet rest, they are at once recognized as the feeble remnants of once vaster extensions.† Therefore at the outset is established the fact that glacial conditions even within the tropics have been much more extensive than at present. Consequently there confronts us at once the problem of accounting for this past extension. The student may start at the base of the great Malaspina glacier of Alaska, lat. 60° N., and follow the evidence of past glacial action into the tropical regions, through the just uncovered plateaux, fiords, and mountains of British Columbia, lat. 50°; through the yet earlier uncovered and fainter traces in the Sierra and Coast Range of California, lat. 42° to 35°; through Mexico,

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**Oldham*, Geol. Mag., Vol. XXIII, 1886. *White*, Am. Geologist, Vol. III, 1889, pp. 222-230. This evidence and its interpretation will be taken up later.

†Russell, Am. Geol. Vol. IX, No. 5, May, 1892. In addition to the extended list of authorities cited by Russell, see also the article of Dufour, Bulletin Soc. Vaud. Sc. Nat., Vol. XVII, 1891, pp. 422-425; Report Brit. Assn., 1881, p. 742; "Life of Agassiz", Vol. II, pp. 717-729, also pp. 743-747. Dr. James Geikie, The Great Ice Age, p. 711 et seq., pp. 721-2 (3rd Edition rewritten), New York, 1895. Dr. Sven Hedin, Through Asia, Vol. I, pp. 292-9 et seq.

lat. 30° to 15°; and even through the barely traceable markings of Nicaraguan glaciers in lat. 12° to 8° N. as noted by Belt, Crawford and Ludlow.

Starting at the confines of the South Frigid zone* the same gradations of distinctness in glacial markings can be traced northward,† until they fade in the highly modified and indistinct evidences within the tropics.

Again, the student may ascend 16,000 to 20,000 feet above the level of the sea in the Ecudorian Andes, or upon Mt. Kenia in equatorial Africa‡, among the dwarfed remnants of actual glaciers doing their work under the same laws as those of Greenland, and from these heights traces the evidences of their work as they grow fainter and older, until they fade into the modified drift of the tropical plains below. At all temperate latitudes where glaciers yet exist, the same gradations of distinctness can be traced in descending to sea level; and as at each latitude and at all altitudes existing glaciers, so far as yet known are retreating, this retreat must be accounted for by known principles now active.

Nowhere is the progress of glacial retreat more distinctly marked than on the west coast of North America. Here the climatic conditions are and have been less subject to fluctuation than elsewhere by reason of the conservative influence of the Pacific ocean. In lat. 40° to 45° on this coast the geologist finds types of topography built up or shaped by ice action, yet so modified or masked by successive generations of forest growths that only the trained eye of the close observer can trace the forms and features. Still farther north and at the same elevation, or even at sea level, the work of the glacier is far less modified and can readily

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**Arotowski*, Sur l'ancienne extension des glaciers dans les regions découvertes par l'expedition antarctic belge, Paris, 1900.

†Explorations in Patagonia. Dr. Francisco P. Moreno. Geographical Jour. Vol. XIX, Nos. 3 and 4, 1889.

‡On Mt. Kenia, 1° S., there are fifteen glaciers the lower limits of which are at elevations of from 14450 to 14900 feet above sea level, the summit being 17000 feet. Glacial boulders occur down to 9000 feet, or more than a mile and a half vertically below the existing glaciers. Geographical Journal, Vol. XV, No. 5, pp. 482-3.

be traced; in the outlying streets of the cities around Puget sound, glacial boulders are abundant and every excavation is in glacial debris.

Throughout British Columbia the forests show distinctly that fewer generations of trees have grown upon the moraines and upon glaciated surfaces than upon those farther south. In southeast Alaska the evidence becomes too absolute and convincing for doubt. The great glaciers of Alaska mark glacial retreat over vast regions and under the conservative influences of the ocean. Single glaciers reaching sea level are far larger than all the glaciers of Europe, and the snow-covered areas feeding the glaciers existing at the base of the St. Elias range are far more extensive than the néves and glaciers of Switzerland. Hence the conditions established by these glaciers are entitled to more weight than any others except those within the polar circles.

Alaskan glaciers which have been retreating for an indefinite period and to very great extents sometimes make sharp temporary advances. The most noted instances of this are the glaciers of Glacier bay. Prof. Muir reports in the publication of the Harriman Alaskan Expedition* that in twenty years, covered by his personal observations, from two to ten miles have been added to the length of the bay by the recession of glaciers. In one instance an island two and one-half to three miles long, in Reid inlet, has been added to the landscape by the retreating glacier.† Yet this group of glaciers advanced in 1899 so rapidly and broke off into such a vast number of bergs that they completely blocked Glacier bay to steamers‡ and it is doubtful whether it will be possible to enter the bay for some seasons to come. A very striking evidence of rapid advance is also given in La Perouse glacier which destroyed a forest growing on its terminal moraines and then receded, leaving the shattered trees as a very positive evidence of the action.§

*Vol. I, page 129.

†Id. page 128.

‡Due to a severe earthquake.

§Harriman Alaskan Expedition, Vol. II, p. 130 and illustration. See also Vol. II, p. 252, illustration of similar action at Columbia glacier.

Despite these temporary advances after centuries of retreat, the retreat is again taken up and in long periods of time is by far the greater, and plant life distinctly records its corresponding gains, although at times temporarily destroyed.

The advance of plant life from temperate towards arctic latitudes is also notable in certain localities; for instance, from Washington through British Columbia and Alaska. Around Puget sound glacial deposits aggregate several hundred feet in thickness; upon these deposits successive growths of forests have built up forest litter and humus, sometimes several feet thick; passing northwards, the evidence of glacial action becomes fresher and more distinct and the forests, although dense and abundant, have a shallower layer of forest litter and humus. Near the base of existing glaciers, and directly in the beds recently occupied by them, the forest trees are young and their advancing saplings and seedlings reach out towards the clean and barren glacial debris as the softer rocks disintegrate and the first indications of soil show themselves. The following case is typical:

Mendenhall Glacier in N. lat. 58° 25′ stands back in a lateral channel putting off northeasterly from the north end of Gastineau channel; it evidently once occupied the whole of this lateral channel to its junction with Gastineau channel. Its base is now some four miles from the junction, and from stakes placed some nine years ago, is retreating at the rate of from forty to fifty feet per year. But this retreat is recorded for a far greater period by the forest and scrub growth in the former bed of the glacier.

At a distance of about two miles from the present face of the glacier the spruce trees are between 200 and 240 years old. The size of one and its growth are as follows:

At	25	years,	9	inches	in	diameter.
"	50	"	16	"	"	"
	75		20½			
	100		23			
	125		25½			
	150		27½			

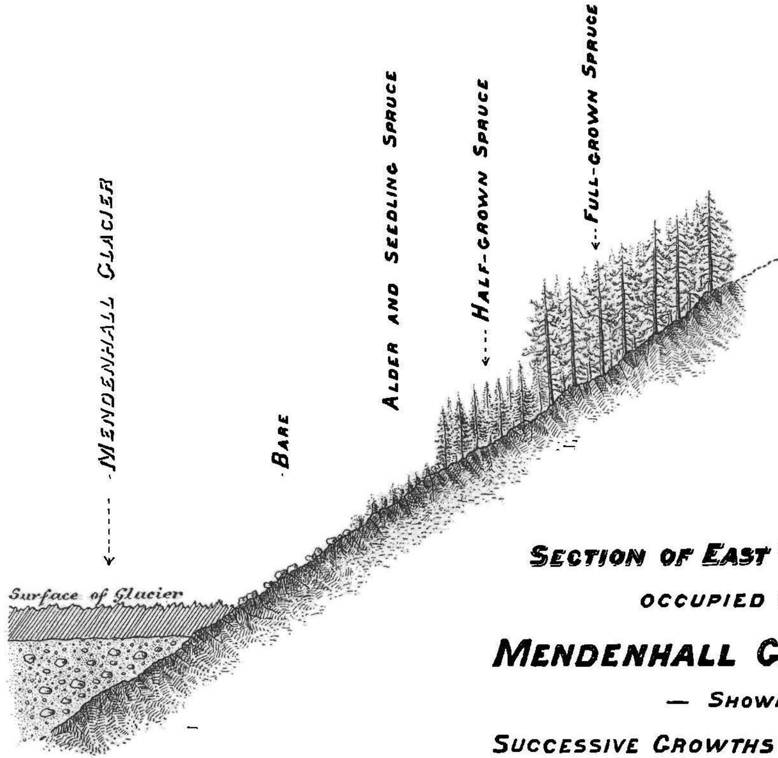
At 175 years 30½ inches in diameter.
" 209 " 32¼ " "

Other trees not felled were as much as eight or ten inches greater in diameter, but the measured tree was about an average. No aged and fallen trees were found. Advancing from three-quarters to one mile towards the glacier no trees could be found over twenty inches in diameter. Within the next half to one-quarter mile the trees had decreased in age to saplings of six to eight inches in diameter, or not over a quarter of a century old. Up to a quarter of a mile from the front of the glacier were seedlings, these giving place to alder brush, dwarf cottonwood, grasses and mosses; when the material within a few hundred yards of the glacier was reached it was found to be clean gravel, boulders and sand. On these but slight signs of disintegration showed, and no growth of any kind appeared except mosses. The rise from tide level to the base of the glacier is about 150 feet (bar.) in the four miles.

Standing at the base of the glacier and looking at the east bank, a very distinct record of the melting and thinning out of the glacier wedge was made by the same process of successive growths of spruce trees. For the first 100 to 110 feet in elevation, the sides of the mountain were quite bare; then a growth of alder and seedling spruce for 60 feet; then a wall of young spruce saplings and poles of 15 to 20 inches in diameter; or about three-quarters of a century old, and 65 to 70 feet above these on a clean-cut and sharp line, stood the dense forest between two and three centuries old. The line of half-grown trees was followed down the mountain slope on the east bank, until it intersected the belt of half-grown trees previously passed through and growing in the flat bed of the glacier.

It apparently takes about one-quarter of a century for the softer rocks to disintegrate sufficiently for spruce trees to begin to grow, thus marking the retreat of this glacier to have been two miles in 300 to 400 years.

The rate of retreat of glaciers at lower latitudes and at greater elevation above sea level has been slower, for here the rise of mean temperatures has been less by reason of



SECTION OF EAST WALL OF CAÑON

OCCUPIED BY THE

MENDENHALL GLACIER, ALASKA.

— SHOWING —

SUCCESSIVE GROWTHS AS THE ICE RECEDES.

— August 1901 —

the decreased density of the atmosphere, and the rate of retreat lessens as the ultimate limit is approached. From the glaciers of Alaska through those of British Columbia the successive retreat of glacial conditions can be distinctly traced in all intervening steps and periods to those latitudes from which this retreat is estimated to have occurred from 5,000 to 30,000 years ago in North America. Corresponding data are found in Europe.*

The conditions of Greenland,† Labrador,‡ Patagonia,§ New Zealand,¶ and South polar regions** indicate that glacial ice is retreating from these regions also.

To speak of the Ice age as a past epoch in the earth's history is therefore not quite correct. Over the greater part of polar latitudes this age is yet in existence at all altitudes; in temperate latitudes the areas over which its present existence extends are more restricted and are confined to elevations between 4,000 and 12,000 feet, according to latitude; in the tropical zone a still greater restriction as to area and altitude exists, glaciers being found only at heights above sea level approximating 14,000 to 20,000 feet. It is therefore possible to speak of it as a past age only in a somewhat restricted sense; and the evidence of progressive retreat found at the base of existing glaciers justifies the opinion that it is a passing age.

The significance of this progressiveness of retreat must be kept constantly in mind, for it bars out of consideration the use of hypotheses and suppositions as to depression being the prime cause of glacial retreat, and upheaval, a

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*Am. Geologist, Vol. XXVIII, pp. 234-240, and authorities there cited. Prof. Warren Upham.

†Of these glaciers Prof. R. S. Tarr observes:—

"In several of the valleys visited by different parties, evidence of former greater ice extension was found, in the presence of moraines, both marginal and terminal, beyond the present ice margin." Am. Geologist, Vol. XIX, No. 4, p. 263. See also Jour. of Geology, Vol. VII, No. 7, pp. 655-666, Thos. L. Watson.

‡Prof. Geo. H. Barton, Am. Geologist, Vol. 15, pp. 379-382.

§Geog. Journal, Vol. XIX, Nos. 3 & 4, 1899.

¶Am. Geologist, Vol. XXVIII (1901) pp. 271-281, Dr. C. H. Hitchcock.

**Arotowski, as quoted on p. 17.

prime cause of glacial extension; and holds the investigation of the cause or causes of this retreat within the lines of causes now active, not only in temperate latitudes of both hemispheres, but within the polar circles.

Upon one point, however, regarding the past extension of the ice of the Ice age, there is much disagreement—namely, the extent of glacial action between the tropics. This disagreement is, however, no greater than that which prevailed during the two decades succeeding 1837, regarding the glaciation of temperate land areas, over which it is now generally admitted that ice flowed in sheets measured by thousands of feet in thickness.

The contests over the evidences of Quaternary glaciation have thus been shifted from that occurring in temperate latitudes* and are now confined to that in tropical latitudes.†

It is gratifying to the searcher for truth that this gradual progress has been made and that each step has been contested, for the naked truth would at any earlier stages of scientific development have been received with incredulity.

There are admitted difficulties in tracing and determining the action of geological forces in tropical areas, which are due to the earlier removal of glacial conditions, to the shorter duration of the period of glaciation, to long exposure to the decomposing effects of tropical rains and heat, and to the commingling of the different classes of phenomena. Although there appears to be no serious question raised as to the occurrence of glacial action within and adjacent to the tropics during the Permian period, yet Quaternary glaciation in these latitudes is strongly disputed. It will, therefore, be necessary to review the evidence and conclusions on both sides.

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*Switzerland, Germany, France, North American States, New Zealand.

†Gibraltar, Palestine, North Africa, India and Chili, South America, Central Africa, Tropical Islands. See Journal of Geol., Vol. I, No. 8, pp. 752-772. Glacialists' Mag., Vol. II, Nos. 5 and 6, pp. 90-114.

Opinions adverse to Tropical Glaciation.

Of the observers who have studied the geology of tropical regions, the following, among many others, may be cited as having expressed views adverse to the idea of tropical glaciation: Charles Darwin,* Branner,† Gardiner,‡ Wallace,§ Orton,¶ Mills,** Derby.††.

Of these, Branner may now be accepted as the leader, since his long residence in Brazil, extended studies and publications justly entitle him to this position; and his conclusions have been accepted by Wallace, an able student of glacial physics.‡‡

Besides these, there are many able observers and writers who are loth to accept any views or interpretations involving tropical glaciation, because no natural law has been cited to explain how solar energy could have been arrested and tropical glaciation occur.

Opinions favorable to Tropical Glaciation.

On the other hand, Agassiz,§§ Hartt,¶¶ Belt,*** De la Beche,††† Blanford,‡‡‡ Schomburgk,§§§ Chardin,¶¶¶

*Trans. Geol. Soc., Vol. VI, 2nd Series, p. 427. "Geological Observations," N. Y. 1891, p. 428.

†Trans. Am. Phil. Soc., Vol. XVI, pp. 419 and 420. Nature, Vol. 48, Oct. 19th, 1893, pp. 589 et seq. The Journal of Geology, Vol. I, No. 8, pp. 753 et seq.

‡New Phil. Jour., Edin., XXX, 1841, 75-82.

§Nature, Vol. 48, Oct. 19th, 1893.

¶Proc. Am. As. Advancement Sci., Vol. XVIII, p. 198.

**Am. Geologist, III, p. 361.

††Quart. Jour. Geol. Soc., Vol. XIII, 1887, pp. 457-573.

‡‡Nature, Vol. 48, Oct. 19th, 1893. See also authorities cited by Branner, Jour. of Geology, Vol. I, No. 8, p. 771.

§§"Journey in Brazil."

¶¶"Physical Geography and Geology of Brazil."

***"The Naturalist in Nicaragua," p. 265.

†††Trans. Geol. Soc. London, Vol. 2, 2nd Series, pp. 182, 186.

‡‡‡Quart. Jour. Geol. Soc. London, Vol. XXIX, pp. 493-503.

§§§Royal Geol. Soc., p. 178.

¶¶¶Travels in Persia.

Crawford,* G. F. Scott-Elliott,† Gustav Eisen,‡ Edward Bedloe,§ and Ludlow,¶ have all observed post-Tertiary phenomena within the tropics, which are attributed to glacial action.

In addition, traces of glacial phenomena which occurred during the Paleozoic and Mesozoic eras,** have been observed in sub-tropical and tropical latitudes to an extent which necessitates their recognition by any one who would attempt to explain glacial conditions.

The strongest proof of tropical glaciation is, however, given by Branner. In order to show how accurately he has described the drift phenomena of Brazil, the two following quotations are introduced:—the first is from "Elements of Geology," 2nd Ed., pp. 546 and 562, by Le Conte.

"THE MATERIALS.—DRIFT.—Strewed all over the northern part of North America, over hill and dale, over mountain and valley, covering alike nearly all the country rock, Archean, Palaeozoic, Mesozoic and Tertiary, to a depth of 30 to 300 feet, and thus largely concealing them from view, is found a peculiar surface soil or deposit; it consists of a heterogeneous mixture of clay, sand, gravels, subangular stones of all sizes, unassorted unstratified, unfossiliferous—"

"MARSHES AND BOGS.—Most of the remains of large herbivores have been found in marshes and bogs * * * * Many very perfect skeletons of the great mastodon have been obtained from the marshes of New York, New Jersey, Indiana, and Missouri—"

The next is from Branner's description of boulders, gravels, cobbles, sand, and clay, scattered over hill and dale, over mountain and valley, in tropical Brazil.††

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*Am. Geologist, Vol. VIII, Nov. 1891, No. 5, pp. 306-314.

†Quart. Jour. Geol. Soc., Nov. 1st, 1895, Vol. LI, No. 204, pp. 675-6.

‡Proc. Cal. Acad. Sci., Vol. V, p. 754.

§U. S. Special Consular Reports on Streets and Highways, pp. 520-525.

¶Report on Nicaragua Canal, 1896, p. 15.

**As elswhere cited.

††See Trans. Am. Phil. Soc., Vol. XVI, N. S., 1889, pp. 421-422. Also Vol. I, No. 8, Journal of Geol., pp. 767-768.

"This formation is spread over the hills and valleys of the Sergipe-Alagoas basin, and over the adjacent country in the form of a thin coating of cobble-stones, pebbles, and sand, sometimes loose and sometimes cemented into a puddingstone as much as ten feet in thickness, and, when exposed, stained black by manganese. It caps the summit of the Tertiary plateaux or their outliers, and is frequently strewn along down the sides of hills, and accumulated in the valleys. It is not confined to the geographic limits of the Cretaceous or Tertiary, but is found further inland and far beyond the present limits of these formations. It is everywhere more or less irregular in thickness, and nowhere can it be said to be universal or continuous. The writer has seen this material throughout the Sergipe and Alagoas, in Parahyba, and as far inland as the headwaters of the Rio Ipanema in the interior of the province of Pernambuco, where there is no remnant of stratified Tertiary beds."

"Between the lower Rio Sao Francisco and the frontier of the province of Pernambuco, this water-worn material is found mingled in bogs with the remains of extinct gigantic mammals."

"One of the marked characteristics of this post-Tertiary formation is that it is much coarser inland, and grows finer as the coast is approached."*

Branner accounts for these materials by assuming that at the close of the Tertiary a gradual depression took place.†

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*"If a continental glacier moved down the Andes to the Atlantic we would naturally look for porphyritic boulders scattered over the valley and decreasing in number and size as we near Para." (Sir H. H. Howorth, The Glacial Nightmare and the Flood. Vol. II, p. 495, London, 1893.) Branner has therefore supplied the very evidence which Howorth considers essential.

†Many geologists cite facts showing a slight elevation at the close of the Tertiary as accounting for the cold causing the Ice age. Glacialists' Magazine, vol. I, No. 10, 1894. See also the authorities there quoted by Prof. Upham.

Then a gradual upheaval,* during which the action of waves is accredited with triturating and depositing these materials on hills and valleys, and strewing them down the sides of hills, and in some unexplained way, these cobbles, gravels, and sands get mingled in bogs with the remains of extinct gigantic mammals.

Had Branner been trying to prove the glaciation of the areas described, he could hardly have made the case stronger than he has. It could only be made clearer by tracing the varieties of stone back to their sources; by showing that the deposits were thinner and more modified than similar deposits further from equatorial regions by reason of the shorter duration of glacial conditions, and the greater time and exposure to modifying agencies; by giving the species, food, and habits of the extinct mammals, comparing them with the corresponding animals elsewhere abundant during the cold temperate periods preceding the Ice age, and by showing that their extinction was caused at the same time and by the same agencies which are known to have elsewhere obliterated cotemporaneous life.

But suppose we accept Branner's interpretations of the origin of Brazilian drift as correct, we are nevertheless confronted by glacial phenomena in other tropical countries,† and by the greater glacial extensions in the Andes and other equatorial ranges of mountains, which do not yield to a line of argument, to say nothing of the enormous glacial action in the temperate zones, the accounting for which is only different in degree; for which purpose able geologists reverse the order of upheavals and depressions suggested by Prof. Branner.

The same conditions which would arrest the effect of solar energy and permit the gradual chilling of the globe from ultra torrid temperatures at all latitudes, down successive

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*This is a reversal of the order of upheaval and depression shown to have taken place elsewhere, and appealed to by many geologists as the cause of a similar deposition of drift in temperate latitudes; it will be seen by examining any standard physical atlas that the coast of Brazil adjacent to the mouth of the Amazon is generally conceded to be gradually sinking.

†See instances previously cited.

gradations until the temperate and polar regions were gripped in ice thousands of feet thick, and until the oceans of all latitudes were intensely cold, would not except even tropical land areas.

Review of Evidences of Glaciation.

The varying degrees of distinctness of glacial evidences are so important in their bearing upon the climatic evolution now in progress upon our planet, that at the risk of repetition they must be reviewed. Cold temperate areas show unmistakable evidence of having but *recently lost their covering* of glacial ice.

Near the base of glaciers within the torrid zone and upon less elevated lands in warm temperate latitudes, the same distinctness of recent retreat can be observed. At or near sea level in regions near the polar circles, as in Alaska, Greenland, northern Europe and Asia, Patagonia, South Georgia, Belgica Strait, etc., this retreat has been so recent that it is within the range of history, and in very elevated tropical lands, in less elevated temperate lands and in polar regions glacial ice yet rests, and is yet retreating.

The writer therefore accepts the far greater extension of glaciers in tropical latitudes during the present era as an established fact, and leaves to future examinations the determination of the limits to which Quaternary glaciation extended. It is not essential to the purposes of this paper that these limits should be exactly defined.

The Temperate Age.

It will not be necessary to review at such great length the evidence which goes to establish the extent of the temperate climates which prevailed during neo-Tertiary times. These evidences are as universally accepted as their distribution is wide.

At a period just antedating the Ice age fossil life has everywhere recorded the existence of a warm temperate age. The life systems attest that a temperature corresponding to the warm temperate zones of today existed throughout both hemispheres.* Even in Brazil the remains of extinct gigantic mammals, corresponding to the fauna found in North America, Europe and Asia have been found in bogs mingled with boulders and gravel.†

This, the Tertiary period, is subdivided into three epochs, the earliest of which is sometimes found to merge into preceding tropical conditions through a "transition epoch," although generally the passage is "non-conformable." A marked characteristic of the record made by Nature's thermometers—vegetable and animal life—is that the temperature was practically uniform at and near sea level through the whole range of the present widely varying zones of life.‡

The life in Siberia recorded the same temperatures as that on the shores of the Mediterranean; life in Alaska was of the same nature as that in Brazil or Patagonia; Tertiary life, so far as yet known, establishes beyond reasonable controversy, that from Point Barrow in N. lat. 71° 20′, to Terra del Fuego in S. lat. 55° 40′, or through 127° of latitudes, practically uniform tropical temperatures existed at sea level. Over this same range of latitude there now exists every climate and every type of life, at sea level, from arctic to torrid and back again to arctic. So that the fact is of record that there were no zones of temperature—particularly was this the case with marine fauna and flora.§

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*Dana's Manual of Geology, 4th Ed. p. 792, for types of warm temperate life which flourished in arctic regions.

†Journal of Geology, Vol. I. No. 8, p. 767, as previously referred to. In citing biological evidence tending to show that Brazil has never been glaciated, Branner fails to explain how or why these animals became extinct—although he attempts to show in the face of his own observations to the contrary, that there has been an unbroken succession in tropical life in Brazil since the Tertiary (p. 770 of work cited).
This extinction occurred since the Tertiary. It is at least probable in the absence of definite proofs of some other cause, that these animals became extinct about the same time and through the same agencies by which corresponding life became extinct elsewhere.

‡Dana's Manual of Geology, 1895, p. 939.

§Manual of Geology, Dana, 4th Ed. p. 872.

The Tropical and Torrid Ages.

During the Mesozoic and Palæozoic eras there existed much warmer temperatures than we have just reviewed for the Temperate or Tertiary period. It would be useless to cite, to even the youngest students of geology, the facts which would be massed to prove the universal distribution of the tropical plants of the Carboniferous period* or of the warm water marine life of the Silurian period.†

The manuals and text-books of geology are overburdened with instances and illustrations. Underneath the strata of these ages lie the previous strata of the Cambrian and Laurentian, beneath which lie in turn the enormously thick, non-fossiliferous rocks of the pre-Cambrian and Azoic eras—the border land between geology and cosmology. The minerals composing the rocks of these earlier eras, like those of later ages, are presumably the worked-over materials of previous ages, the traces of which are buried beneath the strata of all subsequent time,‡ and a study of which carries us into the pre-geological ages of cosmology.

We are taught alike in the text-books of the common schools and in the profound treatises of geologists and physicists that during these ages, the earth "was a melted fiery ball, surrounded by a thick atmosphere of gases and vapors. In the course of ages this fiery ball cooled off, and the solid crust of rock wrinkled and cracked and was thrown into ridges and valleys."

"Meanwhile the waters condensed and ran into the hollows. The interior is still hot but the crust is now so thick

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*Manual of Geology, Dana, 4th Ed., p. 711 Climate of the globe nowhere below 60° F.

†Manual of Geology, Dana, 4th Ed., p. 574, Marine species the same from 30° to 82° N.

‡It is well to note here that of the total land area less than 3 per cent is covered by lava, or molten materials from which the heat has partially escaped by conductivity. Beneath these lava-covered areas lie all strata antedating the Quarternary period. From but a small fraction of the known geological strata has the earth heat finally escaped except by denudation.

that but little of the interior heat escapes. The present heat of the surface is derived almost entirely from the sun."*

Of this stage of the earth's climatic development, Sir A. Geikie says: "At an early period in the earth's history, the water now forming the ocean, together with the rivers, lakes and snow-fields of the land, existed as vapor, in which were mingled many other gases and vapors, the whole forming a vast atmosphere surrounding the still intensely hot globe."†

We therefore accept the view that however wide may be the disagreements as to the origin of the heat of this planet, the records of the earliest life attest a uniformly distributed highly torrid climate, and particularly is this the case as regards the oceans. It is beyond reasonable controversy that this was a stage which had been reached from a previous stage of greater heat.‡ The earth in this condition was a cooling spheroid rotating in space. Its young oceans were warm and their bottoms were in contact with a yet cooling crust. The first recorded period of the history of a planet therefore is one during which its own interior heat influences its surface temperatures and warms its oceans throughout their entire depth and extent.

The great lessons distinctly recorded by fossil life are (1) that there was a non-zonal distribution of temperatures during and preceding the Ice age, distinctly different from the zonal distribution now prevailing; (2) that successive ages of cooler and cooler climates followed one another, culminating in a general Ice age.

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*This quotation is introduced from an elementary textbook on Physical Geography. Warren's New Physical Geography, p. 11. Edited by Dr. Wm. H. Brewer of Yale.

†Text Book of Geology, p. 33, London, 1882. See also Essays, Prof. T. S. Hunt, p. 40.

‡The writer is aware that this view was entertained by Hutton and Werner during the latter part of the 18th and first part of the 19th century. He is also aware of the fact that it has not been successfully controverted since.

It may be denied that this condition was reached within the period of recorded geologic time. Such a condition must in that event have existed at a previous time if our present ideas of the development of the earth be accepted.

Between the widely separated periods just reviewed—the remote pre-Cambrian and the present—there has existed a series of climates beginning with an age of ultra-torrid temperatures and ending with an age during which elevated lands at all latitudes were loaded with ice hundreds and even thousands of feet thick. During each one of these series there was at sea level a uniform distribution of heat from pole to pole; during some of these climatic eras, and notably during the later ones, ice formed at all latitudes, but no life of arctic habit has been found in the strata of these eras; during the last of the series of climates, glacial conditions reached a maximum and *marine life of arctic habit first appeared,* and extended into middle latitudes, from which it has since retreated to higher latitudes.

Upon the close of this series there was inaugurated an era of zonal distribution of temperatures distinctly controlled by solar energy and embracing in one era the extreme range of temperatures, torrid, tropical, temperate and frigid, of the pre-glacial eras of climates. Since the inauguration of these modern conditions there have been and yet remain in force activities which have caused a very marked rise in temperatures throughout middle and low latitudes, and the limits of action of these activities appear to have not yet been reached.

During the earliest eras earth heat was undoubtedly a factor in surface temperatures and probably the controlling factor; during the present it is no longer an appreciable factor; there lies between the two, the period during which the one source of heat lost its influence and the other source established itself in absolute control. This "transition epoch" was too important a one not to have recorded itself in marked terms. This was probably the most important transition epoch of geologic time.

IV.

ICE FORMATIONS IN THE EARLIER GEOLOGIC AGES.

Their Significance. Criteria and Definition of an Ice Age. Has more than one Ice Age occurred?

It is now admitted, by nearly all geologists that an ice age has but recently been passed through. This general acceptance has developed a new branch, almost a new school of geologists, and glacial geology has been specialized into as distinct a branch as any other of that science. Some of those who have taken up this new branch have not only found reasons for subdividing this ice age into glacial and interglacial periods, but from the evidence of ice action in earlier eras they have built up a succession of ice ages or glacial period—each new horizon which reveals evidence of ice action being cited as proof of an ice age.

Since these evidences of ice action have been discovered in low latitudes and in different geological eras, it has become necessary to account for them, even though ice ages have to be introduced between the torrid and tropical climates recorded by fossil life. It is even regarded by many as the test of a theory to account for the Ice age, that it should be sufficiently flexible and comprehensive to admit of successive ice ages; and any theory which fails to account for these earlier ice ages is relegated to the list of failures. This is done to such an extent, and, has been so seldom traversed, that it becomes necessary to define the terms *ice age, glacial period* or *epoch.* It will be necessary to frame this definition on broad yet rigid lines—broad enough to clearly embrace and define the essential criteria, yet rigid enough to prevent the use of the term in the face of contradictory facts, or without sufficient justification and data.

Before attempting to frame such a definition it may be well to review the conditions which existed at the culmination of the Ice age of recent times. These conditions are widely known and quite generally accepted.

Conditions in the Northern Hemisphere.

At the culmination of that age the Laurentide glacier extended in an unbroken flood from the mouth of the Ohio lat. 37° N. to lat. 65° in the valley of the McKenzie, and from the Pacific ocean in lat. 47° to the Atlantic in lat. 40°, covering not less than one-half the continent of North America.

Every range of mountains beyond these limits from Costa Rica and Nicaragua to the Arctic ocean shows evidences of ice action; and from nearly the entire continent there were obliterated a previously existing warm-temperate flora and fauna—life having survived in certain protected areas, which escaped glaciation. The most notable of these are "the unglaciated area" east of and including portions of the Columbia Lava Plain,* and portions of the drainage basin of the Colorado and adjacent territory in the Humboldt basin.

In corresponding latitudes, Europe was buried beneath the Scandinavian ice flood, from Ireland to the east base of the Urals, and from the White Sea almost to the shores of the Caspian. The ranges of mountains beyond these limits, the Alps, Jura, Pyrenees, Caucasus and Atlas were flooded with vast glaciers which flowed over the valleys and into the plains at their bases. Further east into Asia, it appears that glaciation was light except on the mountains. Throughout Siberia it is probable that glacial ice could not accumulate to the extent that it did in Europe, for the reason that the air was deprived of its moisture to form the great Scandinavian ice sheet, and descended upon the plains of Siberia comparatively dry. But from this vast region there disappeared a previous warm temperate flora and fauna. The mountains—the Hindu Kush, Himalaya, Kuen Lun, Altai and Stanavoi ranges,—all present evidences of having been glaciated to their bases. Of polar lands it is unnecessary to speak. The land masses of the northern hemisphere were either deeply glaciated or chilled to such a degree that the temperate life distributed over

*The writer has endeavored to explain the causes of this escape under V of this paper.

them was either destroyed or developed into hardier types, which survived and spread when milder conditions supervened.

During this period of extension of land ice, the life in the oceans of the northern hemisphere marked a degree of cold never before attained. This low temperature was reached only after successive ages of slowly falling temperatures, which were distributed over land and sea without regard to latitude, and at variance with now existing climates.

Conditions in the Southern Hemisphere.

The land areas of the southern hemisphere have not been studied and mapped so closely as those of the northern. Hence the past conditions as geologically recorded are not so well known. The largest areas—the continents of South America and Africa, present phenomena in their southern portions similar in every respect to the glacial phenomena of corresponding latitudes in the northern hemisphere. The equatorial regions of both present many ranges and peaks upon all of which glacial action has extended to much lower altitudes than at present, and the great plateaux and coasts are marked by types of topography and other phenomena which indicate vast glacial action under the rain belt of the equator. From these lands, as from admittedly glaciated areas, the flora and fauna of the warm temperate age preceding the Ice age, have disappeared. Even in equatorial Brazil cobbles and gravel are "found mingled in bogs with the remains of extinct gigantic mammals," just as they are found in admittedly glaciated countries. The general types of topography bear the characteristic glacial features of lands in temperate latitudes.

Throughout Australia and New Zealand, and even the oceanic islands of the southern hemisphere, such as Kerguelen and South Georgia, vast glacial extensions have been explored and reported. All existing glaciers show evidences of having extended to far greater proportions than they now reach.

So far as the temperatures of the great oceans of the southern hemisphere have been studied, as recorded by the life which has existed in them, these temperatures have been on a gradually decreasing scale, until the culmination of the Ice age, with an increase in temperature in middle and low latitudes since that period.

All data yet collected on the subject indicate that these great extensions of glacial conditions were synchronously imposed, or nearly so; and that the retreat has been a progressive one from equatorial regions polewards, and from sea level upwards; and no phenomena yet discovered tends to weaken the interpretation that these great glacial extensions were the result of conditions affecting the entire globe.

The conditions, therefore, which characterized the Ice age of recent times were:

(1) An accumulation of snow and ice upon land areas exposed to maximum precipitation, and upon all elevated lands. A great lowering of the snow line and the imposition of temperatures sufficiently low to destroy or radically modify previous life-forms of temperate habit, and the development of marine and land life of boreal habit.

Resulting from the action of vast flowing masses of ice and their variations in flow, were forms of topography characteristic of ice action, the deposition of quantities of ice-borne and water-worn material, the striation of rock surfaces in place and in transit, and the dropping of erratic masses of stone hundreds of miles from their places of origin.

(2) In the oceans a gradual lowering of temperatures to nearly glacial conditions, and a corresponding, but not so well marked extinction of pelagic life of temperate habit; and by the development, for the first time, of arctic and cold temperate forms. The distinguishing characteristics of this Ice age were therefore:

(1) The appearance of forms of life fitted for boreal or arctic temperatures and developed from the more adaptable species of older temperate forms, themselves developed in turn from previous life of a still warmer habit; and the de-

struction of other forms; this applying to both land and marine life.

(2) The deposition of sheets of ice of continental extent and reaching sea level, which developed types of topography shaped by the action of ice or built up of ice-borne and partly water-worn materials transported to vast distances from their origin.

(3) Striated and polished rock-surfaces.

(4) A distribution of rock masses by flowing ice, marking the limits or the direction of flow.

Of these the most positive and convincing characteristic was the development of pelagic life of cold temperate or arctic habit—for land temperatures are readily affected by elevation, by remoteness from warm winds; and, owing to the low specific heat of land and air, are more subject to variations than oceans; so that even the forms of life developed upon land are not so reliable as those developed in the oceans, which, by reason of the high specific heat of water are not subject to rapid or temporary variations.

The phenomena indicative of ice action, although impressive beyond measure in their extent and mode of occurrence, are not so convincing as the gradual marking of lower and lower temperatures by the forms of life, and the obliteration of those forms which were unable to cope with conditions just preceding and accompanying the Ice age. An attempt will now be made to frame a definition of such an ice age.

AN ICE AGE *is a period in the climatic history of a planet when its oceans chill to that degree which permits the development of life of cold-temperate and arctic habit; and when its land areas, particularly those exposed to maximum precipitation, are flooded with ice descending to sea level, and those areas not so exposed are reduced to so low a temperature as to destroy or modify the previous warm-temperate life. Antedating the approach of such an age, there must be a gradual development of forms of land and marine life suitable to temperate conditions.*

The requirements of this definition will now be applied to the evidences indicating ice action during the Palæozoic and Mesozoic eras. These evidences have been very carefully collected and ably presented by Mr. R. D. Oldham* of the Indian Geological Survey, and also by Mr. C. D. White† of the U. S. Geol. Survey. These authorities cite numerous examples of ice action during the Carboniferous and Permian periods occurring near to and within the tropics, principally in the lands bordering the Indian ocean. These evidences are, in most instances, indisputable and are apparently contradictory of the proofs of warm temperate and tropical climates within the polar circles during these periods. Nor are these apparent contradictions the only ones, for alongside of the ice-borne boulders there occur fossils indicative of warm-temperate and sub-tropical climates.

Very significant and positive facts thus apparently stand opposed to one another. 1st. Ice action in tropical latitudes during eras in which tropical life flourished near the poles. 2nd. This ice action took place near warm-temperate land and sea life.

On the assumption that the climates of those ages were controlled by solar energy, and that temperatures were zonally distributed these phenomena are indeed inexplicable. If climates had been disposed in zones during the Palæozoic and Mesozoic eras, a "glacial period" in tropical latitudes with Carboniferous plant and animal life flourishing in polar latitudes would indeed demand a "change in latitude" of from forty-five to ninety degrees. But if we accept as true, what fossil life abundantly proves, that prior to the Ice age there were no *zones* of climate, and that climatic variations were dependent solely upon altitude, the formation of ice in or near the tropics, or at any latitude whatever, is not contradictory nor confusing in any manner, but in simple accord with the principles controlling the distribution of temperature as regards altitude.

**On Homotaxis and Contemporaneity.* Geol. Mag. N. S. Decade III, Vol. III, p. 293-300 (1886). *Probable Changes of Latitude.* ib. pp. 300-308.

†*Carboniferous Glaciation.* Am. Geologist, vol. 3, 1889.

Applying the foregoing definition to the ice phenomena of the earlier geologic eras, we find that whilst some of the conditions appear to have been fulfilled, there were other highly important ones which were not. There were undoubtedly accumulations of ice from time to time, particularly in low latitudes. Existing forms of life were destroyed, especially at the close of the Permian. But there was a significant absence of preceding cold-temperate life and notably of marine life of this habit, indicating that the oceans were yet warm. The most essential and characteristic requirements of the definition do not appear to have been fulfilled. It does not appear, therefore, that a full justification exists for accepting evidence of ice action as sufficient to establish the occurrence of an ice age. It is, however, sufficient, and in some instances incontrovertibly so, to establish the existence of ice as a geologic agent. Ice evidently formed in sheets of great area, flowed in accordance with the slopes and conditions of deposit, striated rock surfaces, and deposited boulders and gravel; and, as in the Permian ice sheets, it may have destroyed the land life of the period, and even have reached sub-tropical or temperate seas and deposited ice-borne boulders alongside of warm-temperate or sub-tropical life.

The writer therefore holds that there are as yet, insufficient data to justify the conclusion that the earlier evidences of ice action indicate ice ages or glacial periods. But these early evidences of ice action prove beyond question that land masses were thrust up above the then existing snow line. This snow line, for reasons given elsewhere, may have descended to lower elevations for a given sea-level temperature than at present. The absence of cold-temperate or arctic forms of pelagic life is too significant to justify the opinion that there has been a succession of ice ages, or "changes from cold to warmth and back again to cold." The nearness of some of these early glaciations to the equator substantiates the view herein maintained that prior to the culmination of the Ice age, temperature-distribution was independent of latitude, and that variations in temperature were caused principally by difference in elevation. The uniform distribution of fossil life establishes this beyond reasonable controversy.

That the glacier was a geologic agent during the Cenozoic and Mesozoic eras may be admitted, but that an Ice age or Glacial period occurred during these eras is by no means proven.

But once in geologic time have the oceans chilled to about the point of maximum density of water, and but once have continental glaciers descended to sea level and reached that extent which justifies the use of the term Ice age.*

V

The Distribution of Rainfall and its Relation to Glaciation.

Rainfall is principally distributed in three zones. These belt the earth near the equator and near latitude 50° N. and 52° S. These zones are generally designated as the equatorial and the north and south temperate rain-belts. Between those of temperate latitudes and the equatorial belt are the dry belts in the latitude of the tropics. The positions of these rain and dry belts are better defined on the westerly shores of continents than on their easterly shores; this is due to the fact that on the east shores of continents the dry belts are interrupted by minor, oblique rain-belts, the positions of which are determined by warm oceanic currents, which impinge against the continents on that shore in equatorial latitudes, and turn northeasterly and southeasterly along the shore lines and across the oceans. These currents are apparently caused by the equatorial winds, which move in the same direction. The currents turn as above described, but the winds continue westwardly and

*The acceptance of ice action alone, as definite proof of an ice age or glacial period appears too much like attempting to write the details of a man's life, and their bearing on contemporaneous history, upon finding a stone on which a name had been carved—a work which would draw largely on the imagination, but which would be devoid of serious interest to the student of history.

carry with them the heat and moisture which interrupt the continuity of the dry belts on the east shores of continents. The influences of these oblique belts of rainfall are seen in the moist climates of the southern and eastern part of the United States and in China, which are in the latitude of Lower California and the Sahara. There are corresponding interruptions in the south tropical dry belt on the east coasts of South America, Africa and Australia. These interruptions are intensified by the low barometric pressures which prevail during the summer over continental areas. In addition to these irregularities, others are imposed by geographic and physical causes.

The distribution of mean annual rainfall upon the accompanying map of the world is from the latest and best authority on that subject—the Atlas of Meteorology, elsewhere referred to. Upon this map are shown:—the mean annual rainfall, the hyetal equator, and the approximate center lines of the north temperate and equatorial rain belts. The center-line of the north-temperate rain-belt practically coincides with the line of maximum storm frequency as determined by the International Meteorological observations of 1878-87.* That of the equatorial rain-belt is defined by the lines of maximum rainfall between the tropics. The south temperate rain belt lies across the extreme end of South America, and touches Cape Town and New Zealand; elsewhere it is beyond the zone of definite observations.

Figs. 1, 2 and 3 are selected sections which serve to illustrate this zonal distribution of rain and dry belts.† The data for these figures are taken from Plate 18 of the Atlas of Meteorology‡ by J. G. Bartholomew, F. R. S. The legends

*Bulletin A., U. S. Weather Bureau. Washington, 1893.

†Similar sections through the easterly sides of continents, or on the 80th meridian W and 110th meridian E, would serve to bring out the interruptions in the tropical dry belts, due to the turning of the equatorial currents to the north and south and finally northeasterly and southeasterly across the oceans. These interruptions are quite fully shown on the accompanying map.

‡Vol. 3, Physical Atlas. Archibald Constable & Co., Westminster, 1899. Published under the auspices of the Royal Geog. Soc.

on each sheet give the general location and scheme of these figures.

The rainfall on the west coast of the two Americas, on the west coast of Europe and Africa, and through the median line of the Atlantic ocean are shown in Figs. 1, 2 and 3, respectively. From these figures a composite curve is derived, shown on Fig. 5.*

In these figures it will be observed that the equatorial rains are north of the equator by several degrees.† This is due to the greater amount of solar energy received by the northern hemisphere in its longer summer, to the relation of the land to sea, and to the influence of winds and ocean currents which carry into the northern hemisphere some of the heat and moisture which they receive in the southern.

It is known that the zones of rainfall and of aridity are subject to seasonal oscillations of several degrees in latitude, due to the obliquity of the plane of the ecliptic to that of the equator, which obliquity causes the zone of vertical rays and the zones of maximum absorption of the infra red rays to shift seasonally from their summer to their winter positions.‡ These movements are within moderate limits and serve to distribute precipitation over broader belts than would occur with less obliquity of the plane of the equator to that of the orbit. These movements are, however, only indirectly connected with the problems now being considered.

These belts are persistent over land and sea, and their seasonal positions are controlled by the vertical sun, which causes them in some regions to move from land to sea and from sea to land. So far as present data reveal them, the

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*It is not intended that this figure should include the rainfall upon meridians on which the distribution in belts is interrupted by continental influences and by the irregular oblique belts of rain on the east coasts.

†See also any standard physical atlas, and particularly the Atlas of Meteorology, just referred to. It will be observed that the thermal and hyetal equators are both north of the geographic equator, and that the mean annual isotherm of 68° F. in the northern hemisphere is about four (4) degrees farther from the geographical equator than the corresponding isotherm in the southern hemisphere.

‡See Vol. I, Annals of the Astrophysical Observatory of the Smithsonian Institution p. 216.

positions and oscillations of the south temperate rain belt are as well defined in the water hemisphere as are those of the north-temperate rain belt in the land hemisphere. They are as regular in movement on the oceans as they are in the interior of continents or on precipitous shores; and would apparently be as regular were the relative areas and positions of land and oceans to change places. It is therefore manifest that these belts are the result of principles whose action is not materially interrupted by local conditions, although these may extend or restrict, increase or diminish the relative degrees of rainfall or of aridity.

The distribution of rainfall being distinctly influenced, if not caused by solar energy, could not have been suspended during geologic time, and although the conditions of action may have varied, the influences of solar energy in the upper regions of the atmosphere could not have been suspended. Solar influence may therefore have fixed the lines or zones along which the moisture should be precipitated, by fixing the zones of maximum vertical circulation under the influence of vertical rays and of maximum absorption of oblique rays.

We are now prepared to compare the distribution of rainfall with the distribution of glaciation.

The distribution of drift in North America, Europe and a small portion of extreme northwestern Asia has been quite closely studied and mapped. The extent of this distribution has been previously outlined, but for purposes of a very brief and general comparison it may be well to reconsider this distribution with reference to the loci from which it took place. As mapped by geologists, glacial dispersion in North America occurred from two principal "centers of dispersion"; these were about the intersections of the Rocky Mountain plateau and the Labrador Range with the north temperate rain-belt. There appears to have been a general dispersion from about the 50th parallel southward into the basin of the Mississippi, and northwards into the basin of the Mackenzie; the extreme limits of this distribution being the 37th and 65th parallels.*

On the Eurasian land mass the flood of glacial ice reached its maximum height where the summit of the Scandinavian peninsula was intersected by the north temperate rain-belt. From this intersection as a center of dispersion, glacial ice flowed in all directions; crossing the German ocean, it overspread Scotland, England (except the southwest portion about Devon), Ireland, the Baltic Sea, and all of northern and western Europe to about the 50th parallel, having an extension into southeastern Europe nearly to the banks of the Volga at Tzaritzin, in lat. 48° 45′ thence northerly to Nijni Novgorod, and northeasterly across the Urals in latitude 62° It is probable that the moisture taken up in the air passing over the Atlantic was quite effectively condensed in crossing the Scandinavian Alps and the Urals, and this air descended upon the great plains of Siberia deprived of its glacier-forming power. Hence these plains may not have been subjected to that degree of precipitation which would flood them with ice.

The extent of glaciation in central and northeastern Asia has not yet been fully mapped. Elsewhere there are given some of the data which are known, showing that all ranges of mountains (especially those subjected to heavy precipitation) were covered with glacial ice; and that upon all the higher peaks and ranges dwarfed remnants of these glaciers yet rest.

Evidences of glacial action within the limits of the equatorial rain belt are widely distributed, but no extended nor definite studies of them have been made. All existing glaciers show evidences of greater extent. Some of the most

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*Consult *The Great Ice Age.*—Prof. Jas. Geikie. The Ice Age in North America—Prof. G. F. Wright. U. S., State, and Canadian Geological Surveys.

notable localities at which glacial action has been observed are indicated upon the map.*

Under the south-temperate rain belt past glacial action of great extent has been noted. The west coast of South America from 35° south to Terra del Fuego has been deeply glaciated, and the islands of the southern hemisphere, such as Kerguelen, Falkland, South Georgia and New Zealand are marked by glacial action of far greater extent than now prevails.†

This general occurrence and dispersion of ice is shown in blue upon the accompanying map of the world.‡ An inspection shows that in the northern hemisphere the zone of maximum depth of glaciation and of glacial dispersion practically coincided with the center line of the north-temperate rain-belt; and that from this belt glacial ice flowed into regions of less precipitation. Corresponding dispersion from other belts of rainfall into adjacent regions of less precipitation can now only be inferred.§

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*It may be said generally of evidences of glacial action within the tropics that only when these evidences are of a very broad and definite nature have they been acknowledged as glacial. The standards of comparisons have been developed in north-temperate latitudes, and many of these standards may not exactly fit the phenomena of tropical latitudes. When the modifications of longer time, tropical rains and heat, and the probably shorter period of glaciation are better understood it may be found that glacial dispersion also occurred from the equatorial rain belt into adjoining belts of less rainfall.

†Existing glaciers in the south-temperate regions reach sea-level much nearer the equator than do those of corresponding north-temperate latitudes; and as previously noted, those of New Zealand, although nearer the equator, are of far greater extent that those of Switzerland.

The land areas which reach the south-temperate rain belt are so limited that they cannot give the general data which are obtained under the north-temperate rain belt.

‡The data upon this map relating to the occurrence of glacial phenomena are taken from the authorities quoted throughout this paper, especially from the works of Prof. Jas. Geikie, Prof. G. F. Wright, the U. S., State, and Canadian Geological Surveys, and the Journal of the Royal Geol. Society.

§It is possible that the continent of Africa may show such dispersion northerly into the Sahara, and southerly into the arid regions of South Africa.

It is manifest, from a comparison of rainfall distribution, that maximum glaciation during the Ice age occurred in regions over which maximum rainfall now prevails; and that in the northern hemisphere glacial dispersion occurred from about the center line of the belt of north-temperate rains.

(NOTE)—The Unglaciated Area in the United States.

Probable Cause of the Escape.

In the deposition and southerly flow of ice in the central and northwestern part of the United States, there was an extended interruption. This interruption is remarkable, and is, in a measure, of moment in the present discussion. It will, therefore, be briefly described. An area situated in parts of the States of Oregon, Washington, California, Idaho, Montana, Wyoming, North and South Dakota, and aggregating many thousands of square miles in area, escaped invasion by the Laurentide, or great continental glacier of North America. This glacier flowed towards the unglaciated area from the north and northeast, was apparently stopped by the Missouri river, and flowed up to and against this barrier from the intersection of the 47th parallel with the 110th meridian to the mouth of the Ohio river in latitude 37 degrees; a distance of over 1,200 miles. The term "unglaciated area" is not strictly applicable to all of the region escaping overflow from the Laurentide glacier. For within this area are many evidences of "local glaciations" and portions that escaped entirely. The local glaciations were, however, not connected with the Laurentide glacier except by probable synchronism and unity of cause.

Occupying a very irregular shape and lying across the median line of the North American land mass is the great Columbian Lava plain.* This lava plain occupies portions of the slopes of the Rocky, Sierra, Warner, Butte and Cascade ranges of mountains, and of the intervening valleys and plains. This region is exceedingly broken and lies in the States of Washington, Oregon, Idaho, Wyoming, Nevada and California, and is about 200,000 square miles in area. Its greatest length, from the headwaters of the Big-Horn river in Wyoming to the base of the Coast Range in Oregon,

*It is interesting to note that the fractures from which this vast outburst occurred lie about the median line of the extreme limits of the North American land mass, and that about 180 degrees from these fractures similar fractures occurred near the median line of the Eurasian land mass, giving rise to the great Deccan lava plains of India.

is through 15 degrees of longitude; and its greatest width is through 9 degrees of latitude. The maximum thickness of the Columbian lava is known to be 4,000 feet, and many square miles of this thickness can be observed. Vertical sections of marked distinctness can be studied in the cañons of the Columbia river and its tributaries, and in the old channels known as the Grand and Moses coulées. The aggregate length of deep river cañons and deep coulées which can be observed is several thousand miles, so that opportunities to study the formation and character of the lava are remarkably good.

The walls of these cañons are made up in some places of as many as thirty successive layers of lava superimposed with varying intervals of time, as the joints are sometimes very distinct with no evidences of denudation nor sedimentation; while at other localities there are intermediate strata which are sedimentary and fossiliferous. The layers are rarely over a few hundred feet thick and overspread subdivisions of the total area sometimes at close and sometimes at widely separated intervals. Traces of volcanic heat yet remain, as is evidenced by the existence, at numerous localities throughout the area, of hot springs, fumaroles and heated earth. In the Yellowstone Park there are several thousand vents for hot water, gases and boiling mud. Although numerous extinct craters exist in the area, the slopes of the lava plain are such as to preclude the view that these were the main sources. The main outflow must have been from vast rifts probably concealed, or at least undiscovered. Irregular and unequal movements of the crust have occurred since the outflow, so that the present slopes do not always coincide with those upon which the lava flowed. The character of the lava varies in successive layers and in different localities; and in some instances directly overlies Tertiary formations.

In its more elevated portions, particularly in the western part, evidences of late local glaciation occur. To the north and west, glacial action of enormous extent and energy is noted. To the southwest, in the Sierra, glacial action is also of great extent. Southerly, glacial action is more scattered and "local," as are the irregular lava outbreaks extending through the adjoining states into Mexico.

To the east lies that remarkable and interesting feature, the "unglaciated area." In this area are the "bad lands" of Dakota, full of beds of Tertiary fossils in a perfect state of preservation. Glacier ice has never invaded this area, for not only are the most delicate fossils left untouched near the surface of the softest rocks, but every topographical feature is characteristic of the denuding agency of water. The topography is marked and peculiar; while denuding agencies have been active at all times since the Tertiary, never has the grinding, moving glacier shaped the bluffs into rounded hills, nor filled the valleys with gravels, sands and clays. On all sides except the western lava border, the mighty tread of the glacier has ground down and buried every pre-glacial feature. The great chain of moraines, erratic blocks, kames and kettle holes which traverses the continent, skirts its northern border, but before turning south, retreats easterly for 8 degrees, and then practically follows the course of the Missouri river southeast to latitude 37 degrees, near the mouth of the Ohio; there it turns to the northeast and crosses the rest of the continent to Cape Cod in 42 degrees north. Within the limits of the area thus enclosed on the north and east by evidences of vast glacial action, and on the west by the great lava plain, the gentler forces of water and air have alone shaped the topography; and within its borders are found abundant stores of fossil Tertiary life.

Although snow usually covers the whole area in winter, never did it accumulate so as to mould the rounded hills and slopes, which are so characteristic of glaciated countries; and although the winter temperatures fall far below zero Fahr., the summers are warm and frequently characterized by intensely hot periods.

Whilst glacial denudation and markings are thus wanting, there is no evidence to show that since the Tertiary, the streams have ever ceased to carve their vertical walls and to fill the valleys below with water-borne sediments. That this area should have escaped glaciation by reason of less elevation is not tenable, for more southerly areas towards which both glacial ice and water flowed were deeply glaciated. That it should have escaped glaciation by reason of less precipitation is again inadmissible, for the massive Laurentide glacier, although reaching to the mouth of the Ohio, was limited by the Missouri, which for many hundred miles flowed against its base, and but rarely yielded more than a few scores of miles to its advance. On the north, the great glacial dispersion from the belt of maximum precipitation flowed towards it, and forced its way around the eastern border of the unglaciated area to the mouth of the Ohio in latitude 37 degrees N., or 8 degrees nearer to the equator than to the pole. We must therefore confront the problem of its escape in its broad, bold form. Why should rain have fallen on the unglaciated area, whilst snow accumulated to enormous depths all around it, except on the lava beds to the west, and flowed towards this area from the north?

Assumptions of unequal rainfall, and unequal upheavals have been appealed to as causes for the escape of this area from glaciation. Unequal precipitation could only have affected the relative depths of glaciation, but could not cause an escape, and could in no way have checked the flow of the great continental glacier. To have remained at a lower level, whilst adjacent areas were sufficiently upheaved to cause glaciation, would have accelerated rather than retarded glacial flow from the north and northeast; consequently, these hypotheses complicate rather than explain the phenomena.

The presence of the great chain of glacial material extending from the intersection of the 47th parallel and the 110th meridian, southeasterly to the intersection of the 38th parallel with the 89th meridian must be accounted for by showing that there were positive conditions causing the precipitation upon the unglaciated area to be rain instead of snow, and stopping or warding off the glacial flow from the north.

We have in the vast heat escaping from the Columbia lava plain, a cause starting before and continuing long after the Ice age had departed from this latitude. The influence from this heat must have locally affected climatic conditions at all periods of intervening time, and these effects must be recorded in that area most exposed to their influence, namely, to the east, since this is the direction of atmospheric circulation.

The interpretation which the writer offers of these facts is simple. That these eruptions commenced in Tertiary time, is indisputable: the heat brought into the outermost strata of the crust in the vast inundations forming the Columbia lava plains yet remains in noticeable quantity, and must have been a factor in local climatic phenomena during the Ice age. The manifestations of this heat in the geysers of Yellowstone Park profoundly impress the investigator and illustrate one of the ways deep-seated heat escapes from a forming crust. The present phenomena could all be compassed in a square mile and are insignificant in energy when compared with the manifestations which for ages have characterized the greater portion of the entire area now covered by lava measured by thousands of feet in thickness.

To no other cause can we reasonably attribute the checking of the great Laurentide glacier in its mighty invasion than to the warm air and rain, which continually passing over and falling upon the lava plains, made the Missouri a warm river during the Ice age. Although therefore there was an apparent break in the continuity of the deposit of glacial ice along the zone of north temperate rains, this break can be readily explained.

VI.

The Premises and the Solution.

In the brief review made under II., of the principal theories urged by various scientists as causes producing the Ice age, it was remarked of the first, that it was universally admitted as true, and even taught in elementary works on physical geography, but that it failed to account for all the facts developed by the Ice age and later climatic phenomena. This first theory was a decrease in the original heat of the globe, the truth of which is established by a mass of indisputable geological evidence. Authorities were there cited to show that the original heat of the globe had been abandoned as a cause of climatic variation. Now it is not logical to admit that earth heat was at any time a climatic factor, and then to abandon it as such without fully considering: (1) its functions and relations to exterior sources of heat; (2) the modes of bringing it into activity, conserving and utilizing it in the performance of work, and the results of these processes in connection with the exterior source of heat; (3) the approximate period of its final exhaustion and of the establishment of solar climatic control.

Then, too, this abandonment was made before a full understanding was had of certain very vital functions of the atmosphere, which have an important control over the modes and rates of receipt and loss of radiant energy and heat. It has been necessary therefore to review the basis of this abandonment—namely, the mathematical calculations of the duration of earth heat and to point out that certain great and important factors had been omitted in these calculations, which omissions threw grave doubts upon their results and upon the propriety of accepting them as premises in the problem.

Under III, an epitome was made of past climatic conditions. These were traced back into the earliest geological period. At which period it is universally conceded that earth heat was a factor in surface temperatures.

The occurrence of glaciers in the earlier geologic ages was considered under IV., but it was not found that such occurrences were accompanied by cold-temperate nor boreal life, nor by cold seas, and the conclusion reached was, that these glaciers were local and due to elevation, and did not justify the conclusion that they represented an Ice age, any more than do the present glaciers on the east slope of the Andes, which are in sight of sub-tropical verdure. Under V., the relations between the distribution and depths of glaciation to the zones of rainfall and of aridity were briefly reviewed.

These reviews thus epitomized are here referred to as premises and as facts to be accepted and accounted for in accordance with the data outlined and the generally accepted conclusions. We therefore accept as a premise that at the dawn of geological time two sources of heat influenced the climatic conditions of the earth. It is necessary to note the peculiar function of each, and to mark the date of the sensible extinction of one and the establishment of the other.

The mode of heat distribution during the existence of earth heat must have been so different from the distribution after it ceased to be one of the two sources, that nature may be depended upon to have definitely recorded within reasonable and positive limits the epoch when it ceased to act as a sensible factor, and although there may have been "fluctuations in this dying energy," it may be possible to plainly fix the epoch of the transition. We must note also, that there were two distinct cooling surfaces, one land and the other water; the latter having a very high specific heat, the former a comparatively low specific heat and a more intense rate of radiation. A marked difference in the rate and time of cooling must therefore be looked for, water cooling much more slowly than earth and rocks. Water was also a prime agent through which the land parted with its heat. In addition to this, it appears in three distinct forms, each of which possesses remarkable properties in its relation to heat and cold, and to radiant energy.

It is universally admitted that this original heat has been lost to such an extent that it is no longer a sensible factor in the surface temperature of the earth, and that solar energy is now the controlling source of heat.*

*See also Manual of Geology, Dana, 4th Edition, p. 258.

There can be, then, no mistaking the first nor the present condition of the earth as regards its exposure to the two known sources of heat—(1) solar and stellar energy*, and (2) resident, internal or earth heat. There must have been two marked eras of climatic control—(1) a past era, during which both sources were active; (2) the present era, in which the greater exterior source only remains, the local and lesser source having been largely exhausted.

Or, in other words, we have, *first,* a heated globe having resident in its mass a finite quantity of heat undergoing loss, yet sufficient to maintain equable temperatures of a torrid degree, and exposed to an exterior source of radiant energy, which may be considered sensibly constant during the eras under consideration; *second,* the same globe deprived of this equably distributed heat to such an extent that the outer surface is exposed only to solar energy and radiation into space, subject to the conservative functions herein noted, and whose climates are controlled thereby. The objects in view are to explain (1) the peculiar uniformity of climates, prior to the practical exhaustion of the equably distributed source; and (2) the occurrence of an age of general glaciation. independent of latitudes, prior to the zonal distribution of temperatures under the control of the exterior source; (3) the reasons of the difference between heat distribution during geologic and present climates.

To be more explicit, the prime objects are to demonstrate:

1. That in the passage of the earth from an era during which its climates were controlled by dual sources of heat into an era during which its climates are controlled by solar energy alone, eras of uniform climates must have been passed through during which isotherms were independent of latitude; and elevation above sea level was the prime cause of local climatic variation.

2. That before climates could pass under solar control, an age must occur during which elevated continental areas

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*Stellar energy having the same function as solar energy, and being sensibly a constant of unknown amount but much less than solar energy, need not be separately considered in the further discussion of the question.

must be glaciated; and that this phenomenon, occurring before solar climatic control, was also independent of latitude.

3. That the direct cause of the Ice age was a combination of the remarkable properties, in relation to heat and cold, possessed by the various forms of water. As water, by reason of its high specific heat, it longer retained the effective remnant of earth heat; in passing from the liquid or solid form into invisible vapor its high specific heat makes it the most effective cooling agent known; as vapor and in the form of fogs and clouds, it largely prevented the loss of heat by radiation, or the receipt of solar energy; as ice, it assumed a solid form, storing matter at a low temperature.

We may therefore state the problem in the form of a proposition in which we accept as a premise that the internal or earth heat was present to a sufficient extent to maintain the oceans at the torrid temperatures * indicated by the fossil life of the earliest geologic era—having reached this stage from an earlier era of probably greater heat.

The General Proposition.

GIVEN: A heated globe, constituted and circumstanced as the earth admittedly was and whose surface, by reason of internal heat, is at a torrid temperature, to prove that before its surface temperatures can pass under the control of solar heat (1) climatic changes must be independent of latitude, and (2) that continental areas must be glaciated.†

It will be observed that a globe thus situated and whose surface is for the greater part covered by oceans warmed by internal heat, must be shrouded in clouds, and that its surface temperatures are almost wholly controlled by its internal or

*This temperature is used as the basis of this argument because it is about that degree which the earliest fossil life shows to have prevailed throughout all portions of the world yet reached by the geologist. Theoretically, a far higher temperature may have prevailed, and probably, did prevail, during the cosmic life of the planet; but the actual existence and source of this heat, and its degree, have not yet been determined with sufficient exactness to serve as a basis for the subjoined discussion. Therefore, only that degree of surface temperature, or that climatic condition, which fossil life proves to have existed, is accepted.

†See note at end of V, p. 46.

earth heat; for, between such surface and any external source of energy, there must intervene a dense cloud surface, maintained by the evaporation due to internal heat. The fact that direct radiation is almost entirely intercepted by fogs and clouds, is well known;* therefore, the surface of a globe thus situated is protected against serious loss by radiation of its own heat, and against direct exposure to radiant energy from exterior sources.

The functions of the two sources of heat were thus peculiar and distinct. Interior or earth heat was utilized near the surface in maintaining temperatures and in the evaporation of water. Solar energy was utilized by absorption in the upper regions of the atmosphere and upon the outer surface of the cloud sphere. It therefore had only a secondary or conservative function to perform, leaving the control of the surface temperatures of the cooling spheroid to its own supply; or in other words, during its activity, the local lesser source, had the active, dominant function to perform; and the greater source of exterior energy was relegated to the secondary or conservative function of partly replacing the heat lost by radiation into space from the outer, cold surface of the enclosing clouds.†

By the conditions of the problem presented, we thus have a globe having resident in its mass a finite quantity of heat exposed to loss principally by means of the gradual conversion of water into vapor, which with warm air would rise in convection currents and be exposed to loss of heat by radiation from its upper surface into space. This vapor would then condense, and as rain, snow or hail, descend all, or part of the way to the earth, take up another increment of heat and ascend and condense as before—a slow process, but exhaustive in time, although retarded by the conservative action of exterior sources of radiant energy.

Thus, the property of water to assume three forms, each of which possesses remarkable qualities with regard to heat,

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*Maury, Physical Geography of the Sea, 6th Edition, p. 212, et seq.; Croll, Climate and Time, p. 60, et seq.; also Climate and Cosmology, p. 51; Geikie, the Great Ice Age, pp. 800-801.

†See note at the end of this section.

afforded the principal means for exhausting the earth heat. As vapor, it possesses with one exception,* the property of storing more heat than any other known substance, and of being when partly condensed, the least transcalent medium known; the high specific heat of water, in the shape of clouds or fogs, largely prevents heat from traversing the atmosphere until the minute vesicles be expanded into invisible and transcalent vapor. As a fluid, it possesses the highest specific heat of any substance composing the crust of the earth; and as snow or ice, it possesses the property of storing more cold than any other known substance. Clouds being more translucent than transcalent, light rays reached the planetary surface more readily than heat rays.

The earth may be regarded as having been surrounded by a series of spheroidal isotherms of mean temperature. The one next the surface represented a mean temperature of say 100° Fahr. Above this isotherm were others representing mean temperatures of 80°, 60°, 32°, zero, etc., to —x° Fahr., the extreme cold of interplanetary space.

Between the two spheroidal isotherms of 32° and —x° Fahr., was one which had a mean temperature of 32° —y°, and equally exposed to both sources of heat.

That the spheroid of 32° Fahr. was within the sphere of prevailing influence of earth heat, is proven by the formation of snow or ice at that temperature, both being the resultant of vapor expanded and raised by earth heat to that height as a minimum. Moreover, vapor would have reached that height with no partial conversion of exterior sources of energy into heat.

It therefore follows that the isotherm equally heated by both exterior and interior sources was colder than 32° Fahr., or below that temperature at which snow and ice form. It is also well-known that solar energy does not maintain a temperature as high as 32° Fahr., except in the lower and denser regions of the atmosphere.

The isotherms nearest the earth were spheroidal in shape, and by reason of the conditions their surfaces were practically

*Hydrogen.

parallel with that of the earth; those most remote from the earth, by reason of solar influences, flattened at the equator and protruded at the poles, so as to be slightly less oblate than the earth. Hence, near the equator, the direct action of the sun was first felt and established.

As the effective and controlling earth heat was a finite quantity exposed to loss, it was in time exhausted. As this loss proceeded, the spheroidal isotherms of mean temperature shrunk in upon the earth, and their contacts with its surface marked the distribution of corresponding climates prevailing during the dual source of heat. Since the inner isotherms were largely independent of equatorial or polar exposure to solar energy, their contacts with the planetary surface established climates practically independent of equatorial or polar position, or of latitude; and not until those depending upon solar energy shrunk to the surface, could climates ranged in latitudinal zones be established. As the climates established by the contact of the isotherms inside of the one equally heated by earth and sun were independent of direct solar energy, they varied from the climates established later by solar energy alone; hence the marked difference between climates antedating and succeeding the Ice age. The isotherms preceding this age were dependent almost entirely upon elevation above sea level, fractures, and conductivity of the earth's crust, and were therefore non-zonal; those succeeding it are dependent upon proximity to the equator but are modified by elevation above sea level, and the distribution of heat by ocean currents, and are therefore zonal.

At the expiration of a certain period of time, the earth lost sufficient heat to cause the isotherm of 80° Fahr. to shrink to the surface except at fractures, and a uniform, moist and highly tropical climate was established and types of life developed, culminating in the Carboniferous period.

The crust evidently had cooled sufficiently to permit the demarkation of the continental and ocean areas, but the cooling did not necessarily proceed to that point which upheaved the massive mountain ranges, nor greatly depressed the ocean areas. Apparently an era of low, flat continents and shallow warm seas followed. The life of that period abundantly shows this condition from one polar circle to the other, and the prevailing temperature is recorded in the fossil life of the Palæozoic and Mesozoic eras.

The water falling upon heated areas or circulating in the crust would rob these of their heat and carry it in warm or hot streams to the oceans. The vapor evaporated from land areas, would also lower their temperatures, and aid in maintaining a dense cloud formation which would shut out solar energy until the effective remnant of earth heat was exhausted. Not until the bottoms of the oceans were subjected to a degree of cold approximating that to which the continental areas were exposed, could the whole crust be cooled uniformly and attain its present degree of rigidity and stability.*

At the expiration of another succeeding period of time, the spheroidal isotherm having a temperature of say 60° Fahr., similarly shrunk to the surface of the earth, and a corresponding uniformly temperate climate was established.

The further cooling of the crust caused its shrinkage, and a consequent greater upheaval of the lighter areas most exposed to loss of heat, the continents. The areas thus thrust up into isotherms of lower temperatures, might reach the isotherm of 32° and be thus exposed to glacial action at whatever latitude such upheaval might occur.† This further shrinkage caused the strata formed during the previous eras to be upheaved and fractured, and the lines of demarkation between oceans and continents were thus more strongly accentuated.

The life developed in the interim evidences an approach to that of the present warm temperate zones, and its wide distribution indicates the complete control of the climates of the globe by internal heat. The isothermal lines were entirely at variance with those subsequently established by solar energy, therefore the functions of solar energy were principally

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*In cooling, had there been the exposure of one pole to glacial and the other to temperate or sub-tropical conditions as argued by Croll, our planet would have been subjected to very peculiar "cooling strains" as they are termed by foundrymen. Whereas the slow and uniform cooling, as herein described, is productive of maximum thickness, strength and uniformity of crust.

†See under V, pages 46 and 47.

conservative of those operating on the surface during this period also.

The extreme and uniform distribution of fur or hair-covered animals and of the deciduous and coniferous trees of the neo-Tertiary epoch, mark further the control of a source of heat more uniformly distributed than solar energy could possibly be. For reasons previously given, this isotherm also reached continental areas earlier than ocean areas. When the mean temperature of the land was 60°, the tepid oceans must have had a higher mean temperature due to the high specific heat of water and to increments of earth heat received from the crust. Whenever the isotherm of 32° Fahr., shrunk so as to reach the more elevated portions of the continental areas, a snow line was established independent of the influences now establishing and maintaining such snow line. The resulting glaciation was controlled by the same general principles that now prevail, only the distribution of heat being independent of latitude and mainly dependent upon altitude above sea level, glaciation was as likely to occur in equatorial as in polar latitudes; the only requirement was the existence of land at an elevation above the isotherm of 32° Fahr.*

The moment a snow flake reached the earth which successive escapes of the waning earth heat were unable to melt, the Ice age was foreshadowed, and the conditions were such as to favor its extension until the effective exhaustion of the store of heat beneath the oceans and resident in them, by reason of the high specific heat of water.†

From the moment that snow began to accumulate, the remaining earth heat was available for producing those conditions favorable to glaciation, namely, warm seas, dense fogs and cold continental areas, and the solar energy reaching

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*Dark heat rays, or those emitted by the planetary surface, are much more readily trapped than direct or reflected solar rays. Hence, if these dark rays were effectively trapped near the surface during preglacial climates, the snow line would descend closer to temperate or tropical sea level temperatures than under present conditions when the effects of direct and reflected solar energy are added.

†It will be noted here, that whenever, in obedience to the expansive force of this waning earth heat, a particle of water was vaporized and made the last round of its circulation, it returned to the earth in that form which stored the maximum degree of cold, and which it required the action of solar energy to change.

the upper regions of the atmosphere was available for maintaining those favorable conditions.*

Glaciation under these conditions would be cumulative until the oceans, partially exhausted of their heat, and approximately reduced to the point of maximum density, were no longer able to supply the evaporation necessary to screen the earth from direct solar heat.

At the expiration of still another interval of time, the isotherm, having a mean temperature of say 32° Fahr., shrunk in upon the globe, and the oceans were still further exhausted of their store of heat and their bottoms brought in contact with water having a mean temperature of 31° Fahr., a temperature approximating that of the ocean depths at present, and of ice in masses.†

The isotherm 32° Fahr. was a spheroid circumscribing the earth. In shrinking to the earth, its intersections with the surface were controlled by the elevation of the surface above sea level, and by the local escape of earth heat; elevated equatorial or temperate areas were, under this interpretation, as much exposed to glaciation, as polar lands. By reason of the high specific heat of water, this isotherm also reached continental areas, prior to reaching ocean areas.

The crust beneath the ocean, having been protected from loss of heat by the superincumbent water, shrunk approximately to its present shape subsequent to those more exposed portions forming continental areas.

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*The prime objection which is urged against all previous theories is their inadequacy. We have here, it seems to the writer, adequate and potent causes—resident earth heat to maintain evaporation and shut out solar energy, which energy, although shut out from the surface was utilized as a conservator of the heat remaining in the oceans and escaping from the crust. Upon the exhaustion of the available earth-heat, solar energy then reached the surface and became the dominant factor in climatic control and was active in melting ice, and in gradually establishing the present conditions. There is thus brought to bear the heat remaining in the oceans from the beginning of the Ice age to its culmination, and all the solar energy reaching the planetary mass during this period.

†Dr. Jas. Geikie seems almost to reach the same conclusion, for in rejecting the upheaval theory of glaciation he says—"Now it seems easier to believe that the snow line was lowered by several thousand feet than that the continents were elevated to the same extent." The Great Ice Age, 3rd Edition, pp. 792-3.

There might also result a series of crust movements as the continents were weighted down and then relieved of pressure by the melting of the ice caps* and the ocean bottoms subjected to increased pressure by the restoration of water to the ocean.

The continued exhaustion of earth heat in the oceans and beneath them, resulted in the preservation of those conditions most favorable to glaciation—namely, light cloud formations, but sufficiently dense to intercept much solar energy. When by the chilling of the oceans to about 31° Fahr., and by the glaciation of continental areas, the air was cleared of obscuring clouds and fogs, the series of uniform climates was at an end.

The transition epoch—the period of passage from the control of earth heat to that of solar energy is the Ice age. The transition is still in progress, for solar energy has not yet fully established its control,† nor has the Ice age fully departed from the earth.

As in both plant and animal life, certain types foreshadowed through long ages the forms which were to follow, so doubtless, too, in earlier ages, glaciers formed upon the peaks, mountains and plateaus and foreshadowed the Ice age which was to follow when earth heat failed.

When the ruptured and denuded crust ceased to yield heat, to be conserved by the high specific heat of water, then was the Ice age inaugurated in earnest, to culminate when the last effective remnant of earth heat was wrung from that agent most capable of holding it—the oceans.

As the oceans approached their point of maximum density, earth heat ceased to dominate surface temperatures, and thenceforth climatic development has been dominated by solar energy. It is reasonably certain that solar energy first reached the surface of the earth where cloud formations are at a minimum, or in the latitudes of the tropics; for in these latitudes are the loci of maximum downcast currents and of the present dry belts and cloudless areas. It may have been that solar energy penetrated to the surface in these latitudes before adja-

*The Great Ice Age, 3rd Edition, pp. 292-3.

†See IV, pp. 36-40.

cent temperate zones had received their maximum load of glacial ice. It is also reasonably certain that under the vertical rays of equatorial latitudes, solar control was first established in the tropical zone and is still being extended as marked by the vertical retreat of dwarfed glaciers left at great altitudes; that over temperate and polar regions this power is yet being extended as similarly marked by the progressive glacial retreat heretofore referred to.

With the dominion of solar heat there dawned upon our planet an era of climatic zones whose lines sensibly follow parallels of latitude; then also began seasons of spring, summer, autumn and winter, with the varying changes due to the earth's annual round.

The climatic changes during the control of earth heat, and within the range of geological research, therefore extended over these eras:

1. An era of torrid heat. (The Palæozoic)	Non-Zonal.
2. An era of tropical heat. (The Mesozoic)	
3. An era of temperate heat. (The Tertiary)	
4. An era of glacial cold. (The Ice Age)	

These were followed by:

5. An era of solar climatic control. (The Present)	Zonal.

Each merged gradually into the others, and each of the first four, recorded its period of existence in unmistakable terms; all of these were shrouded from the direct action of solar heat, and all of them evidenced by the life produced, the stifling, smothered character of the climate. During each era, glacial conditions could exist locally just as glacial condition now locally exist in the temperate and tropical zones; during each, they could fluctuate as the fading earth heat fluctuated in its outbursts from the forming crust, as changes in elevation took place, or as the great floods of ice were checked, released or changed in their directions of flow. These fluctuations, towards the last, would tend to cause those puzzling "interglacial periods" to the east of the narrow Atlantic, but less manifest to the east of the broad Pacific.

That solar energy was shut out from the surface of the earth during the Ice age, is geologically recorded in the glaciation of the temperate zones over continental areas, where subsequently solar energy removed glacial conditions, and established in their stead a mean annual temperature of 40° Fahr.; in the torrid zone, where it has removed glacial conditions and established a mean annual temperature of 76° Fahr., where now snow never falls.

Consequently, it appears that in a heated globe, constituted and circumstanced as was the earth, exposed to two sources of heat, internal heat and solar energy, before its climates or surface temperatures passed under the control of solar energy climatic changes were independent of latitude and the continental areas were glaciated.

(NOTE.)—The mode of cooling the planetary surface under the conditions just outlined, would be as follows: (1) Heat rays would be radiated from both water and land areas and would be intercepted by the air and clouds; (2) The air in contact with the surface would receive heat therefrom; (3) Rain, snow or hail would fall upon the surface, that portion falling upon land areas in flowing or evaporating therefrom would deprive them of heat in ratios proportioned to the relative specific heats of land and rocks and of water and of the latent heat of water vapor. Rain in collecting and flowing to the oceans would continuously carry heat to them which had been derived from land areas. All of these processes (except the flowing-off of water) would cause convection currents of warm, moist air to rise, which upon reaching sufficient elevation would lose a portion of their moisture by condensation, which portion would again become a cooling agent. Loss of heat, by radiation, into space would be confined to the upper surface of clouds and to the air above this surface, which upper air would not be entirely deprived of its heat-trapping and heat-absorbing powers and would thus be an active conservator of heat to a certain extent.

The processes above named would gradually exhaust the available heat supply by returning convection currents of cool air and of cooling rains and snow.

The warm globe was thus practically within the walls of a constant temperature chamber, in which sea level temperatures were practically constant, and variations in temperature were caused by elevation. There were, however, these essential differences between the constant temperature wall of the experimental physicist and that of the cooling globe:—the constant temperature wall of the physicist is apart from the enclosed materials and is maintained independently of their temperature and existence, whilst the constant temperature wall of highly moist air and clouds enclosed a source of heat, which heat was gradually being brought into requisition to maintain the efficiency of the constant temperature wall. This efficiency was being steadily impaired, as this limited source was being exhausted, despite the action of the conservative functions.

This wall was thus maintained by the fading heat of the globe and was composed in a great part of one of the cooling materials. Through this wall, convection currents of warm moist air carried heat outwards; and it also permitted the condensed moisture and cool air to return as cooling agents. As these functions progressed, the heat maintaining this constant temperature wall and the efficiency of the wall itself were reduced. During its existence, there was going on inside of this great spheroidal chamber, the absorption and trapping of the heat rays emitted by the enclosed cooling surface and all those secular changes known as geological climates. On the outside there was received from exterior sources as a conservator, all radiant energy reaching this planet from the dawn of geologic time to the culmination of the Ice age. Under these conditions, glaciers upon elevated plateaus and mountains were as well protected as was plant and animal life at lower altitudes; and, so long as interior heat was available for the evaporation of sufficient water to maintain a cloud shield, the extension of the glaciers was more favored than was the extension and preservation of life.

Water in whatever form it took, was the receiver and conservator of heat; it, and not the land, received and absorbed heat radiated by both land and water; it was a circulating agent always robbing the land of its heat, and retaining this heat by reason of the high specific heat of water.* It and not the land, received and absorbed solar energy until the culmination of the Ice age.

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*Between the melting and boiling points of water the ratio of specific heat of water to that of earth and rocks is about 1.0:0.19.

VII.

THE CONTROLLING PRINCIPLES OF THE EVOLUTION OE CLIMATES.

The writer has endeavored to show:—That the glaciation of a planet constituted as is the earth, was the direct and necessary outcome of known and generally accepted principles, and the termination of a series of uniform climates controlled by the resident internal heat of the planet; that this heat was subject during its continuance to conservation by clouds and the vapors and gases of the atmosphere; that it was not lost by direct radiation into space from the warm surface of the planet, but by convection currents of warm moist air which carried it beyond the trapping and intercepting power of clouds, from the cold, upper surface of which it was radiated into space; that this loss was in part replaced by heat derived from radiant energy from exterior sources; that upon the close of the series of non-zonal climates the oceans were, by reason of the high specific heat of water, the last areas to cool, and that upon thus cooling, to about the point of maximum density, cloud formation became sufficiently thin to permit solar energy to reach the planetary surface, over which it is gradually establishing its control; and finally, that these processes have constituted a system of climatic evolution, controlled by known laws.

The principles appealed to in support of these views are briefly expressed below in the form of a series of postulates and corollaries. It is believed that they will be generally admitted as true; at all events, anyone can readily satisfy himself regarding them.

The controlling principles of the Evolution of Climates.

(1) Heat rays cannot pass through fogs and clouds, formed of the vapors of a fluid having the physical properties of water, except with very greatly diminished intensity.*

*Maury. Physical Geography of the Sea, 6th Ed., p. 212, et seq. Croll Climate and Time, p. 60. Climate and Cosmology, p. 51. Geikie, J.—The Great Ice Age, pp. 800-801.

(2) A warm spheroid rotating in space and holding water and air (or fluids of similar properties) within the sphere of its control, gives off heat and receives radiant energy so far as they can pass through clouds. The spheroid must lose heat principally by the expansion of water into vapor and indirectly by radiation from the cool outer surface of its cloud envelope, which envelope is maintained by the evaporation of water by the heat of the spheroid, and conserved by exposure to exterior sources of radiant energy; during the existence of the cloud envelope it acts as a conservator of the heat of the spheroid.

(3) That in the stages of cooling, subsequent to the formation of oceans, land surfaces must cool earlier than oceans by reason of the fact that water was a circulating and cooling agent of higher specific heat than earth and rocks;* moreover, heat reaching the planetary surface by conduction by the circulation of meteoric or included water, or set free by denudations, faults, fractures, lava outbursts, &c., was principally taken up by water in its fluid and vaporous forms and conserved by water in the form of clouds.

(4) The surface temperatures of such a cloud covered spheroid must be practically independent of exterior sources of heat until the greater portion of the water surrounding it be reduced to its point of maximum density or converted into ice, and prior to this stage of its climatic evolution, its surface temperatures are practically controlled by interior (or planetary) heat, and are practically independent of latitude; and are therefore independent of the degree of energy to which the outer surface of the cloud sphere may be exposed. The effect of variations in exterior radiant energy would be mainly to increase or decrease the duration of the intérior supply, and to expand or contract the sphere of cloud-condensation, the principal function of radiant energy reaching the outer surface of the cloud covering being conservative, i. e., to replace in part the heat lost by radiation from the cold outer surface of this envelope.

(5) That until the exhaustion of the available internal

*Between the freezing and boiling points the ratio of specific heat of water to that of earth and rocks is about 1: 0.19 as previously given.

heat supply, outside of a crust of low conductive power, the surface temperatures of the spheroid must be nearly uniform from pole to pole, varying only with elevation above sea level, or from local causes, such as the influence of lava outbursts upon the areas to the leeward of such outbursts. And that a series of uniform climates must prevail independent of latitude, and gradually decreasing in temperature as the spheroid loses heat.

(6) That the low specific heat of land areas and more intense radiation permits them to cool more rapidly and to reach glacial temperatures before the oceans are reduced approximately to the point of maximum density, and consequently that snow must accumulate upon these areas until the oceans cease to give off sufficient vapor to shield the earth from solar energy. That these accumulations of snow must reach their maxima along belts of maximum precipitation, and must sensibly be independent of latitude.

(7) That upon the chilling of the oceans to about the maximum density of sea water, the supply of vapor maintaining the cloud envelope is cut off, and the atmosphere is thereby deprived of a considerable portion of its power to intercept radiant energy from exterior sources, which then reaches the planetary surface in sufficient quantity to dominate its climates. A new distribution of temperatures is then inaugurated, dependent principally upon latitude or exposure to exterior sources, and modified by elevation and local causes.

(8) That solar energy by contact with the planetary surface is absorbed thereby and that this surface radiates dark or obscure rays which are trapped,* or are selectively absorbed† principally by the vapor of water and by carbon dioxide in the atmosphere. That a gradual accession of heat must be thereby inaugurated, resulting by continued exposure in the removal of glacial conditions, and that such removal of glacial conditions must be on lines determined by the degrees of exposure to solar energy, and the susceptibility of the different portions

*Tyndall—Proc. Royal Soc., Vol. XIII, p. 160. Phil. Trans., Vol. 152, p. 95. Archives des Sciences, tom. V., p. 293.

†Langley—Investigations on the Action of the Atmosphere on Solar Radiation, Mem. Nat. Academy of Sciences, 1885-7. Buff—Archives des Sciences, tom. LVII, p. 293.

of the globe to be influenced by such exposure. That these new conditions must inaugurate a new distribution of temperatures ranged in zones and subject to solar control.

The corollaries dependent upon these postulates are: (a) That a planet having water and air within the sphere of its control, which has not yet exhausted its internal heat, must be densely shrouded in clouds, whose outer surface presents a high albedo.

(b) That a planet whose internal heat has been practically exhausted, and which holds water and an atmosphere within the sphere of its control, must reflect solar energy deficient in those rays which are most readily trapped, or selectively absorbed by its atmosphere, and it must have a low albedo; and that the color of its reflected rays must be controlled by those least readily utilized and trapped.

(c) That glacial conditions may exist locally during any period of a planet's climatic evolution provided there be regions sufficiently elevated; but that an Ice age occurs as its oceans are finally exhausted of their available remnant of planetary heat; that this age marks the period during which surface temperatures pass from interior to exterior control, or is the transition period of its climatic evolution, and is unique.

(d) There are two great eras in the climatic evolution of a planet; 1st, the era during which its internal heat controls its surface temperatures, and solar energy acts principally as a conservator of interior heat; 2nd, the era of solar control of climates. The former is an era of gradually decreasing temperatures of uniform distribution at sea level; and the latter an era of zonal distribution of temperatures which gradually rise until an equilibrium shall be reached between the rate of receipt and the rates of utilization and loss of energy and heat. The two eras, so far as land areas are concerned, must be separated by an Ice age. The differences in the specific heat of land, and that of water, and the action of the latter as a cooling agent, permit the land areas to cool first. The accumulation of snow upon them must therefore have increased and extended to lower altitudes, until the oceans were reduced to so low a temperature as to give insufficient evaporation to maintain an effective cloud shield from radiant energy.

It is reasonably certain that glacial conditions were first removed from the regions of minimum cloud formation and precipitation adjacent to the tropics, and that maximum glaciation of land areas in temperate latitudes may have occurred subsequent to the inauguration of solar control over equatorial latitudes, and that polar glaciations may have reached their maxima at a period subsequent to the commencement of the disappearance of glaciations in temperate latitudes.

(e) The accession of heat by the trapping process after exposure of the planetary surface to direct solar energy, being the result of a positive difference between the rate of receipt and the rate of loss, and not being entirely a function of the orbital distance, a rise in temperature may as certainly follow for a planet at one distance as another.

(f) That glacial conditions, although imposed upon lines independent of solar energy, must have reached their maxima upon areas subject to maximum precipitation, and as the movement of the atmosphere in temperate latitudes is towards the east, the west coasts of continents are more exposed to moist winds and hence were more deeply glaciated than the east coast. The narrow North American continent was thus more exposed to glaciation from the wide Pacific than was the broad Euroasian continent from the narrow Atlantic.

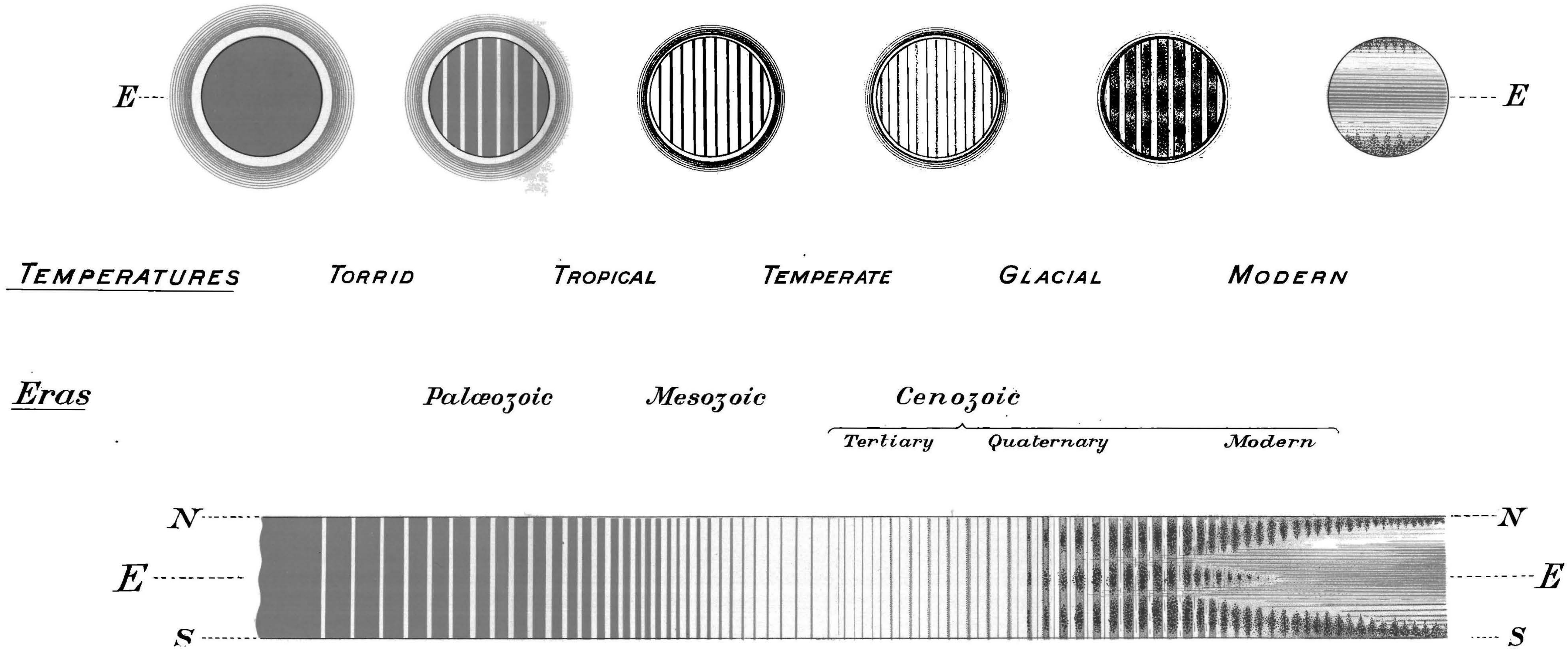
(g) That as the melting of the glaciers occurs from exposure to solar energy, the glaciers of the northern hemisphere have had their gradients and transporting powers increased towards southern latitudes and decreased towards more northerly latitudes, the converse of this taking place in glaciers of the southern hemisphere.

(h) That the northern hemisphere of low specific heat has progressed further in climatic development than has the southern hemisphere of high specific heat. The glaciers of Patagonia are much nearer the equator than those of Alaska, and those of New Zealand, although five or six degrees nearer the equator than those of Switzerland, are far more extensive.*

*Am. Geologist, Vol. XVIII, Nov. 1901, pp. 271-281.

— Diagram —

Illustrating the Distribution of Temperatures at Sea Level



This development of climate is represented on the accompanying diagram. The parallel lines N-N, E-E and S-S represent the lapse of geologic time from the earliest Paleozoic to the present. The fading of the non-zonal temperatures (shaded vertically) into the increasing zonal temperatures (shaded horizontally) is represented by the merging of the vertical and horizontal shadings into one another. This merging commences in the regions of minimum cloud formations, near the tropics, and indicates the inauguration of solar climatic control in those latitudes. The increasing temperatures due to this new control and their distribution are shown in the horizontal red shading on the right of the diagram.

The increase and decrease of glacial conditions under the zones of maximum precipitation are shown in the dark green shading, which also indicates the greater retreat of glacial conditions in the northern hemisphere. At special periods of time, during the various eras, this distribution of temperatures is indicated in the upper circular figures, which are shaded to correspond with the diagram beneath, and are surrounded with neutral shadings indicating the decrease in the surrounding cloud sphere.

VIII.

The Development of Solar Climates.

There remain to be considered two important parts of the problem of climatic evolution, namely:—

(1) How did the climatic conditions existing at the culmination of the Ice age develop into the conditions which now prevail? (2) Towards what state are these new conditions tending? The answer to the first of these questions has been

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Note—It will probably be noted that no mention is made of light rays; these can be filtered by clouds and pass through in greatly diminished intensity. It is not considered necessary to discuss their influence at this point, as their effect is slight at temperature approximating the freezing point. The gradual development of visual organs and the development of all other senses prior to that of sight are lines of investigation which the writer has not followed out.

outlined and foreshadowed under II, III and IV, and in accordance with principles (7) and (8). It may be well, however, in view of the importance of the principles involved, to indicate the process more definitely.

In the foregoing, the development of preglacial climates has been traced from a condition of ultra-torrid temperature gradually chilling down through a series of climates, each cooler than the preceding and each independent of latitude; the last of the series being the Ice age, during which glacial conditions were vastly more extended and lower in temperate and tropical latitudes than they are now. At this period the snow line was much lower than at present, and elevated lands at all latitudes were glaciated, particularly along lines of maximum precipitation; the seas in midde and low latitudes were also colder than at present. It is evident that since the culmination of the Ice age and in the establishment of the present climates, temperatures have risen in tropical, temperate and sub-frigid zones.*

There is also indisputable evidence that this rise in temperature is yet in progress.† This accession of heat must therefore be accounted for by the correct application of known principles and agencies now acting, and to the writer it seems that it is not necessary to go outside of these to render a correct interpretation of the development of the zones of climate now existing.

It may be accepted that at the culmination of the Ice age, earth heat as a climatic factor had been exhausted‡, and that existing conditions have been brought about and are controlled by solar energy.

Upon the exhaustion of the earth heat in the oceans the amount of evaporation from them was reduced and the vapor available for cloud formation, brought to a minimum; or, evaporation being a direct function of the temperature, the

*The exact limits of past glacial extensions in the tropical and temperate regions of the globe may or may not be agreed upon. It is accepted as a fact that these extensions were much greater than at present, and the *cause* of these extensions and of their replacement by present conditions are the subject matter of this paper, not the determination of the limits.

†See under III, p. 15.

‡Most, if not all geologists and physicists at present claim that earth heat was exhausted at a far more remote period than the Ice age. The author is at present unable to accept this view.

two approach and reach a minimum concurrently. As the cloud envelope faded, solar energy reached the planetary surface. The moment a ray of solar energy reached the surface and melted a snow flake, that moment was the removal of the continental glaciers of the Ice age foreshadowed and the process of their removal outlined.

The amount of solar radiation which reaches the upper regions of the earth's atmosphere is estimated to be slightly in excess of 3 calories per square centimeter per minute. Under vertical rays and when the air is clear, about 1.4 calories reach the surface at sea level; oblique incidence or a slightly clouded atmosphere greatly reduces this amount, while thick clouds intercept all direct radiation in the solar beam and absorb or reflect away all or nearly all its rays.* It is probable that not more than one-fifth or one-fourth of the total amount of solar energy intercepted by the earth traverses the atmosphere, the greater portion being absorbed in the outer layers of the air and principally in the visible spectrum. The small fraction reaching the surface is there absorbed or reflected in variable ratios. That portion absorbed by the planetary surface raises the temperature of this surface, which then emits heat rays of a different character from those received, and these are almost entirely trapped or selectively absorbed by the atmosphere. There was thus inaugurated a three-fold mode of warming the lower atmosphere. (1st) By direct absorption of radiant energy; (2nd) by contact with the warmed planetary surface causing convection currents to distribute this heat; (3rd) by the trapping or selective absorption of the invisible long wave length rays emitted by the warmed planetary surface.†

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*The author is indebted to Mr. C. G. Abbot, of the Astrophysical Observatory of the Smithsonian Institution, for this data.

†In developing the generally accepted laws and interpretations of the dynamics of the atmosphere the effects of the greater fraction of solar energy, which is directly taken up in the atmosphere have not been given due consideration and weight.

The smaller fraction reaching the planetary surface has been accredited with preponderating influences. When the effects of each fraction shall be more equitably apportioned very marked changes will take place in the explanations of atmospheric movements and circulation.

See also *Proceedings of the Second Convention of Weather Bureau Officials*, pp. 62-65, Washington, 1902, and Vol. 1, Annals of the Astrophysical Observatory of the Smithsonian Institution, particularly the last paragraph of the preface, page 2, and plate XX.

It would not be possible to show from the measurements yet made whether or not the heat accumulated in the earth by this process has yet reached its maximum. But the results recorded by the progressive retreat of continental glaciers and by the rise in temperature in tropical and temperate seas prove conclusively that it has been a cumulative process. Furthermore, from the determinations of Tyndall and the researches of Langley, Abbot and Very, in this country, and of Arrhenius and other European scientists, it is abundantly proven that it is yet an active factor in climatic evolution. Should further proof be needed, the record of retreating glaciers is indisputable.*

These heat-trapping functions of the atmosphere were pointed out in 1827, by Fourier, and by Pouillet† in 1838. But to Tyndall belongs the credit of determining which constituents of the atmosphere possess this heat-trapping power, and the comparative effect of each. His view that the vapor of water possesses this power to the greatest extent has been recently confirmed by Very—"As an absorbent of terrestrial radiation aqueous vapor is very much more efficient than any other atmospheric ingredient."‡ Upon this point, however, there is not entire agreement, some physicists holding that these two constituents are about of equal power.§ This question is not material for the purposes of the present discussion. It is sufficient that the atmosphere has permanent constituents which in the aggregate possess this heat-trapping power—for it is the action of the atmosphere as a whole that is under consideration. This has been measured to the most minute extent for all parts of the spectrum through the magnificent work of Langley at Allegheny and at the Astrophysical Observatory of the Smithsonian Institution¶; and also by European physicists.

*See Chapters IV and V.

†Comptes Rendus. T. VII, p. 41, 1838.

‡F. W. Very. Bulletin G. U. S. Weather Bureau, Washington, 1900, p. 130. Vol. I Annals Astrophysical Obs. Smithsonian Institution, Chapter VII and particularly pp. 204 and 214.

§See the article by Arrhenius previously quoted.

¶See Vol. I of the Annals of the Astrophysical Obs. Smithsonian Inst. previously cited.

Now, when this heat-trapping or selective absorption process was inaugurated upon the earth, it ceased to be a heat-losing body, and within certain limits it became a warming—a heat-gathering body in space; for its rate of receipt of heat became greater than its rate of loss. A new factor was thus introduced into climatic control—instead of the uniform non-zonal distribution of temperatures in accordance with the laws of cooling solids, there was introduced a non-uniform or zonal exposure to a source of radiant energy, which thereafter dominated climates in accordance with such exposures.

A gradual rise in temperature was thus inaugurated when solar rays were permitted to reach the surface, for they are there practically converted into invisible long wave length rays, which are trapped or selectively absorbed by the atmosphere. This rise must follow whether solar energy be constant or slowly decreasing, the rise being due, not to the actual amount of heat received, but to a positive difference between the rate of receipt and the rate of loss.

The great increase of mean surface temperature in equatorial, temperate, and sub-polar areas can be accounted for by this small but positive difference between the rates of receipt and loss; as has just been shown, this action is yet in progress. This does not imply that the temperature of the earth will forever continue to rise. For, as its temperature rises its own radiation increases, with attendant increasing activities of convection currents in its atmosphere, which carry outward terrestrial heat to be radiated into space. Hence a time will come when the constantly increasing outgo will become equal to the nearly constant income.

Some high authorities on meteorology recognize this state of equilibrium of temperature to be now existing, as may be seen from the following quotation: "It is evident that our planet, considered as a whole, and on the average of many years, loses all the heat that it receives from the sun, but all the details of this process have not been worked out."*

The writer is unable to find any facts to sustain this view—apparently all tend to refute it. The trapping of heat by vapors

*Dr. Cleveland Abbe, U. S. Meteorological Bureau. Am. Jour. of Science, May, 1892, Vol. XLIII, p. 364.

and gases of the atmosphere—the gradual retreat of glaciers in both hemispheres—and the vast rise in temperature since the culmination of the Ice age—all corroborate the deductions just reached—namely, that the mean surface-temperatures of the globe have been and are yet rising by continual exposure to solar energy and by the absorption of heat rays emitted by the warmed planetary surface.

It does not follow that this rise has an indefinite or excessive limit, for besides the restraining influences just mentioned, the oceans as they become warmer are cooled by giving off more vapor. This vapor, when partly condensed into clouds, intercepts solar heat in the upper atmosphere, and the high albedo of the upper surface of clouds reflects a greater proportion of solar energy into space than the darker planetary surface beneath, and the trapping process is less effective.

The vast store of cold in the continental ice sheets has been greatly exhausted; there yet remains the vaster store in the ice-cold depths of the oceans, the conservative influence of which cannot be estimated; for besides the difficulties of heating water from the surface downwards, there yet remains the cooling effect of surface evaporation. There is thus presented the extreme slowness of the methods by which vast changes are wrought. Here are agencies whose results are so slight as not to have been yet detected by thermometric methods—yet recording their effects in the progressive removal of glacial conditions, and in the establishment and maintenance in their stead of zones of tropical and temperate climates.

In this view it becomes possible to trace the steps by which glacial conditions were removed and zones of climate established.

Solar energy first established its control in those zones most exposed to its power—namely, in the cloudless areas of minimum precipitation between the north temperate and tropical rain belts, and between this latter and the south temperate rain belt. In these zones glacial conditions reached a minimum by reason of their being regions of minimum precipitation, and from them solar energy first removed the slight glaciations that formed thereon, such removal probably having been inaugurated before the glaciation of regions of maximum precipitation had reached a maximum. From these zones, glacial conditions were first removed, and this removal continued north and south upon lines sensibly parallel with present isotherms but modified by precipitation and glacial flow.

The data given previously and those available to any student of glacial physics, abundantly prove that the retreat of glaciers is yet progressing—on the west coast of North America it can be followed by decrease in the number of generations of coniferous trees, and by the thinning of humus and of forest litter, and then by the decreasing age of trees, shrubs and plants as they follow up the retreating glacier.* At almost every glacier the tree and shrub are recording its progressive retreat by their advance. Now and then they yield before the irresistible crush of a temporary advance, but in the repeated struggle, plant life gains ground, for the balance is in its favor. Man's abodes follow the plant and from present indications he will, in time, replace the moss of the tundra with rye and wheat.

In considering the astronomical causes, and the physical results thereby brought about, some writers argue that these causes tended to heat the northern hemisphere more rapidly than the southern. Croll and other physicists have so fully discussed this question that there remains but little to be added.

The prime reason, however, seems to have been omitted. It is simply this: the northern hemisphere, containing so large a predominance of land areas, of low specific heat, was more easily warmed under solar climatic control than the southern hemisphere, in which water predominates. This unequal heating once inaugurated would establish currents both of air and water tending to perpetuate this action, reinforced as it is by geographical and cosmical agencies.

When, by this gradual accession of heat, conditions and temperatures resembling those existing prior to the Ice age

*See also the following authorities furnished by Reid, of Johns Hopkins University, *Russell,* Climatic Changes indicated by the Glaciers of N. A., Am. Geol. 1892, pp. 222. Glaciers of Mt. Ranier, 18 An. Rep. U. S. Geol. Survey, Part II. *Wright.* Ice Age in North Am. Chap. III. *Reid,* Studies of the Muir Glacier, Nat. Geog. Mag. IV. Glacier Bay and its glaciers, U. S. Geol. Survey, 16 An. Report, Part 1. *Vaux,* Observations on Illecellewait and Alaskan Glaciers, Proc. Acad. Nat. Sci. of Philadelphia, 1899, pp. 121-501.

were established, we find these new conditions restricted to latitudinal belts sensibly parallel with the equator, but modified by elevation and ocean currents; whereas the corresponding pre-glacial climates were independent of latitude.

By the trapping of heat rays emitted by the warming planetary surface a gradual rise in temperature was inaugurated at that period when, by the exhaustion of the earth heat left in the ocean, the enshrouding clouds were removed. Not until this removal do we find zones of life belting the earth. In these new zones of climate there are being developed higher, nobler types of life, and with the birth of the seasons there was ushered in upon the earth that light which is developing psychozoic life.

IX.

Relations of the Various Theories to the Interpretation now Offered.

We are now in a position to consider the relations of some of the theories which have been discussed under II, to the interpretation of the principles of climatic evolution herein attempted.

Of these theories, *the first and oldest*—A Decrease in the Original Heat of the Globe,* has been made an essential part of the solution now offered and it has been pointed out that the amount of this heat to be dealt with is not only that which could reach the surface by conductivity, but the far greater amounts resident in the oceans, when geologic time began, and set free from the forming crust by denudations, faults and fractures, and by the circulation of included water. This heat it has been shown, could not have been dissipated by direct radiation into space from the warm planetary surface, but was utilized in the performance of work; which work, owing to the various

*The author is thoroughly advised that this theory has been "abandoned" and even regarded as "the least tenable of all theories". He is, however, unwilling at present to share in these views.

functions of the forms of water, interposed conservative conditions reducing and controlling the rates and modes of loss: furthermore the exterior sources of radiant energy served as conservators of the interior heat supply.

The writer has endeavored along these lines to bring into the problem certain important and vital principles, heretofore overlooked or omitted, and to give each of these that weight which its importance merits. Upon these premises, which the writer believes will be generally admitted, he has made an attempt to solve the great problems of climatic evolution on logical and coherent lines.

This argument has resulted in the conclusions:—that earth heat as a factor in climatic control has but recently become extinct; and that solar energy had to play principally the part of a conservator, until the oceans reached a temperature of about the maximum density of water; that the era of solar climatic control has but recently dawned, and that a planet having reached this stage of its climatic development is no longer a heat-losing body in space, but by reason of a direct and continuous exposure to solar energy and through the cumulative action of the heat-trapping powers of the atmosphere it becomes, within certain reasonable limits, a heat-gathering—a heat-storing body. These conclusions appear to the author to have been logically reached, and to have the support of the facts as recorded by fossil life, by the phenomena of the Ice age, and by the development of existing conditions.

That earth heat should have controlled surface temperatures, until the Ice age, is not in accord with views generally held. But once admit that at any period in geologic time it was a factor in climatic conditions, and accept the known action of water in its various forms, and of the other constituents of the atmosphere, and the conclusions herein reached appear to be correct. These conclusions if generally accepted will necessitate radical modifications of some existing teachings, but no more radical than modifications which, from time to time, have become necessary in all branches of science.*

Some of the principles which have been made the basis of the explanations and theories of others, have an important, although minor bearing upon the explanation herein made, and although the writer does not regard these principles as having been prime and controlling factors in climatic evolution, some of them have exercised and now exercise certain influences which must be considered.

The principal of these theories have been heretofore referred to—of these, the second, *variations in the elevation of land*, has exercised and now exercises a certain control in local climatic variations. The advocates of this theory have strong grounds to appeal to it as the all-controlling cause. They have only to point to the glaciers of equatorial regions to prove that at sufficient height above sea level glacial climates exist.† In temperate latitudes the snow line approaches sea level, and finally touches this level at or near the polar circles.

For reasons previously given, namely, the probable absence of direct and reflected solar energy upon the planetary surface, and the ready trapping near this surface of the heat rays emanating therefrom, it is probable that the altitude of the snow line during pre-glacial ages, was less for a given sea-level temperature than now, and that this altitude was then practically the same for all latitudes.

During warm temperate, tropical, or even torrid ages, whenever land was thrust up to or above the then existing

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*These conclusions are radically at variance with the views entertained by the writer at the beginning of these investigations—having been, in early student life, a believer in the upheaval theory of Dana, Lyell and Le Conte, and later having been almost persuaded to the faith of Croll and Wallace. Many of the hypotheses which have been put forward to account for the Ice age and for Glacial epochs have been called forth through the previous introduction and acceptance of the assumption that solar energy controlled the non-zonal climates which prevailed prior to the introduction of the zonal climates of to-day. So long as it was considered necessary to fit a control necessarily zonal in its distribution to a series of non-zonal climates insuperable obstacles were met. Upon abandoning this assumption and admitting the known action of water in its various forms, the conclusions herein presented were reached.

†See also *The Great Ice Age*, Dr. Jas. Geikie. 3rd Ed. pp. 792-3.

snow line, local glaciation resulted from the same laws, dependent in duration and extent upon the time and areas thus exposed, and upon the lower and lower positions of the snow line, until glaciation ensued even at sea level. Geologists have distinctly proven that great variations in elevation have taken place, due to distortions and adjustments of the crust. The elevations due to these distortions must have exposed areas of variable extents to glaciation. But these upheavals and depressions were not the cause of the gradually lower and lower temperatures recorded by pelagic life. Nor could this reasoning explain why the universally temperate sea-level climates immediately preceding the Ice age should be succeeded at this level by tropical climates in low latitudes, by temperate climates in middle latitudes, and yet remain glacial climates near the poles. If elevation above sea level were the sole cause of the coming-on of the Ice age, why should glaciers remain at sea level in polar-latitudes, over areas when in early Quaternary times mild conditions prevailed. The upheaval and depression theory, alone, fails to account for the glacial climate of the Ice age, for the temperate climate of Tertiary times or for the tropical and torrid climates of previous eras. Glaciation during the Ice age, and that yet remaining over the temperate fossils of polar regions, are on far too grand a scale to be explained by local upheavals. For such an explanation would require the synchronous upheaval of land areas in polar, middle and low latitudes over the entire globe. Some geologists finding that upheavals and depressions of the earth's crust have so fully explained many of the intricate problems of that science, and knowing that at certain elevations above sea level glacial climates exist, it is no wonder that they appeal to these same phenomena to explain even those vast changes of climate indicated by glacial action. And only by expanding the assigned cause to that magnitude, which the phenomena of the Ice age require, is its inadequacy revealed. Furthermore, this theory will not explain the rewarming of the continents and oceans since the culmination of the Ice age, nor the disappearance of glaciers without that depression which this theory requires. Nevertheless, the principle remains true that differences in elevation above sea level have been, and remain, efficient causes for local variations in climate, and that such differences were probably more efficient in pre-glacial ages than at present. But variations in elevation are not now, nor have they ever been, the prime cause of those great changes of climate which have been in progress since the dawn of geologic time. The Ice age was not dependent upon the existence of greatly elevated lands, although such lands were exposed to glacial action, at an earlier date, and remain so exposed at present. Thus variations in elevation have caused and now cause local variations in climate which have complicated the problem and seemingly justified the assignment of general effects to this local cause far beyond its possibilities.

The causes assigned by advocates of the third, fourth, fifth and sixth theories have no especial bearing upon the explanation herein attempted, and moreover, have been declared inadequate by high authorities previously cited; the writer sees no reason to question their conclusions.

The seventh theory, variations in the atmospheric content of *carbon-dioxide,* has been briefly referred to under II, and whilst admitting that this constituent of the atmosphere is one of the factors influencing climatic development, it was denied that it of itself was a controlling cause in climatic variations. It now remains to point out, as briefly as possible, the relations this theory bears to the problem of climatic evolution as herein attempted.

The trapping of the heat rays emitted from the earth by the atmosphere has been quite generally admitted for more than three-quarters of a century.* Measurements of this trapping power, as held by the various constituents of the atmosphere, were inaugurated by Tyndall,† who held that aqueous vapor and carbon-dioxide were the principal components having this power, and that the former possesses it to the high-

*See the article by Arrhenius previously quoted. Also Elements of Geology, Le Conte. 3rd Ed. p. 381 et seq.

†Proc. Royal Soc. Vol. XI, p. 100.

est degree. Very, after conducting elaborate experiments and reviewing all the authorities, confirms this view.*

This trapping power relates to the invisible, transparent water vapor and carbon-dioxide, and not to the water vapor *when partly condensed into clouds or fog,* in which form both heat and other rays in the radiant energy from the sun, and dark heat rays from the earth are almost, if not entirely, intercepted. Thus it is not only the transparent vapor of water and carbon-dioxide in the moister and universally warmer atmosphere of pre-glacial ages that we have to deal with, but also the resultant denser cloud formations. Under these conditions carbon-dioxide, whether a fixed or a variable constituent, would have a minor function to perform, and its ability to trap heat rays emanating from the earth would be subject to the far higher control of water in the form of clouds.

Under this control the functions of carbon-dioxide would be divided. Prior to the culmination of the Ice age it *aided* in trapping the dark heat rays emitted by the still cooling planet, and held its waning heat near the surface. In this action water vapor also played its superior part, whilst clouds at a greater altitude dominated the escape of the waning energy and forced convection currents and the ever condensing rain, hail or snow to be the principal means whereby heat was actually dissipated by being carried above the upper cloud regions where conservative functions could not check radiation into space. It is probable that the dull heat rays emitted from the upper surface of the clouds were still further checked by being trapped in the upper regions of the atmosphere by carbon-dioxide, beyond the limits at which water vapor could exist.

If this constituent (CO_2) existed in greater proportion than at present, it became a more potent factor in the conservation of earth heat, and in certain proportions it may have exceeded water vapor in its powers. But prior to the culmination of the Ice age it was called upon to play the part of a conservator of the original supply of planetary heat, and not to trap the dark heat rays emitted from a planetary surface warmed by solar energy.

*Bulletin G., U. S. Weather Bureau, p. 130, Washington, 1900.

After the culmination of the Ice age the conditions began to change. The exhaustion of the effective planetary heat, resident in the oceans by reason of the high specific heat of water, checked the rate of evaporation and the consequent lessened density of clouds permitted solar energy to reach the planetary surface and begin to rewarm it. Then the cumulative process of a gain in mean temperatures was inaugurated, and the melting off of glaciers and the establishment of existing conditions resulted from the continued action of solar energy. Carbon-dioxide still plays its part but is not essential to the rise, for direct exposure to solar energy must heat the planetary surface, and water vapor in the atmosphere must increase as the mean temperature rises. The trapping process, although augmented by carbon-dioxide, would proceed more slowly without it, variations in its amount would vary the rate of the accession of heat, and its absolute absence would check this rate but not suspend the trapping power of the water vapor and the other constituents possessing this power to a lesser extent.

We now see why variations in carbon-dioxide could not change the non-zonal distribution of temperatures of pre-glacial ages into the zonal distribution of today, and how during each of these distributions it played and now plays an important part. During the existence of the dual sources of heat it aided in trapping the inferior source, and held it near the surface. The distribution was non-zonal by reason of the laws of cooling solids. Upon the exhaustion of this source the present conditions of direct exposure to solar energy came about, which, by reason of the varying exposures of the spherical surface to radiant energy, give a zonal, or totally different distribution of temperatures, in which new distribution carbon-dioxide performs corresponding functions. The difference in effects being due, not to variations in carbon-dioxide, but to the radical difference in the conditions.

Carbon-dioxide, whether a variable or a comparatively fixed constituent of the atmosphere, has been and is one of several constituents which possess heat-trapping power. But the principal factor in the trapping and conserving process is, and has always been, water in its various forms. Arrhenius' theory enables us to more fully understand the intricate nature of the problems of climate, and the subtle agencies at work around us, which have affected the profound changes of climate which the earth has undergone; and which are yet active in the evolution now in progress. Moreover, the application of the principles established by Langley, Abbot and Very, therein set forth to the explanation of climatic changes now in progress will require the entire recasting of present views and interpretations of the dynamics of the atmosphere.

Of the various theories heretofore offered as explanatory of the Ice age, the writer accepts:—

1st. *A decrease in the original heat of the globe*—this decrease being controlled by the action of a densely clouded atmosphere and by its heat-trapping powers, and the supply conserved by the action of radiant energy from exterior sources. This principle, in combination with known and accepted laws, the writer endeavors to expand into a cause, competent to explain the entire series of climatic phenomena which have passed since geologic time began.

2nd. As secondary influences, *elevation above sea level* and *the trapping of heat by carbon-dioxide* have both played and yet play important but minor parts,—the former in the local distribution of climate, and the latter in aiding in the conservation of the original supply and in trapping the heat rays emitted from the planetary surface when warmed by solar energy; but neither has been an essential element in climatic evolution, for secular cooling and glaciation, followed by the warming of the planetary surface by exposure to solar energy and the trapping of heat rays emitted thereby, would all have occurred without great variations in elevations and with or without variations in the atmospheric content of carbon-dioxide.

X.

Summary and Conclusions.

In the foregoing an endeavor has been made to outline the climatic changes through which the earth has passed and to establish certain general principles of climatic evolution competent to explain these changes.

In this task, it was found necessary to briefly recall the principal theories which have been framed to account for these changes and to cite the dissenting opinions thereon by Geikie, Bonney, Le Conte, Becker, Wood, and de Marchi. There were then given the writer's reasons for doubting (1) the conclusions based upon calculations of the duration of earth heat as a climatic factor, and (2) the adequacy of variations in atmospheric carbon di-oxide to account for the secular changes in climate recorded in geologic history. The field was thus left comparatively clear to attack the problem on such lines as the admitted facts and principles would allow.

The oldest of all causes assigned, namely—(1) *a decrease in the original heat of the globe*, is not competent in itself to account for the phenomena of climatic evolution. It cannot, however, be successfully denied that at some period in the earth's history its planetary heat was far greater than at present.

Upon this cause and *upon certain highly important and influential principles* seemingly overlooked or omitted in previous discussions, an attempt has been made in this paper to account for the climatic changes recorded by fossil life, by the phenomena of ice action and by the establishment of existing conditions. The results of this attempt are summarized as follows:—

(1) That at the dawn of geologic time two sources of heat were active agents in the control and conservation of temperatures, (a) *earth heat,* (b) *solar energy* converted in the upper atmosphere into *heat.*

(2) That the functions of these two sources were separate. *Earth-heat* controlled surface temperatures during its prevalence, and by the laws of cooling solids was uniformly distributed at sea level; it was held near the planetary surface by the enshrouding media, by which it was trapped and through which it escaped slowly, not by direct radiation, but by the performance of work, namely the evaporation of water, and by convection currents which carried warm air to the upper regions of the atmosphere, from which regions only could free radiation of heat into space take place. *Solar energy* did not directly effect surface temperatures, during the existence of earth heat as a sensible factor, by reason of the intervention of a dense cloud sphere incident to the universally warm oceans whose temperature is attested by early fossil life; but during this period solar energy acted as a conservator of planetary heat by warming the upper regions of the atmosphere and clouds.

(3) That under these conditions, lower and lower temperatures supervened and were recorded by fossil life and ice action distinctly non-zonal in distribution, but varying locally through wide ranges by reason of differences in elevation.

(4) That land areas reached glacial temperatures whenever and wherever they were thrust up above a snow line controlled by earth heat, and that such snow line was in the main continuously lowered but may have fluctuated and was independent of latitude until the culmination of the Ice age. That land areas reached glacial temperatures earlier than ocean areas, by reason of the low specific heat of earth and rocks, their more intense rate of radiation, through the cooling action of rain and snow and by reason of greater elevation. That they were subjected to maximum glaciation along lines of maximum precipitation, and may have escaped all but light local glaciation in regions of minimum cloud formation and precipitation.

(5) That upon the cooling of the oceans, the effective remnant of earth heat was exhausted and cloud formation reached a minimum, permitting solar energy to reach the surface and to assume domination and control of its tem-

peratures; that the climates of such control became zonal by reason of direct exposure to a zonally distributed source, and that these climates gradually rose in temperature by reason of the trapping of heat rays emitted by the warming planetary surface; that such rise is yet in progress as recorded by retreating glaciers and advancing plant and animal life.

(6) That these progressive changes of climate have been in harmony with the principles of climatic evolution herein set forth; and that they are substantiated by the facts of geology and by the phenomena now taking place.

If the eras of climate through which the earth has passed, and the changes now passing before us have herein been referred to their proper principles and correctly interpreted, the "intricate problems which have hitherto baffled the geologist" may prove grander by reason of their simplicity.

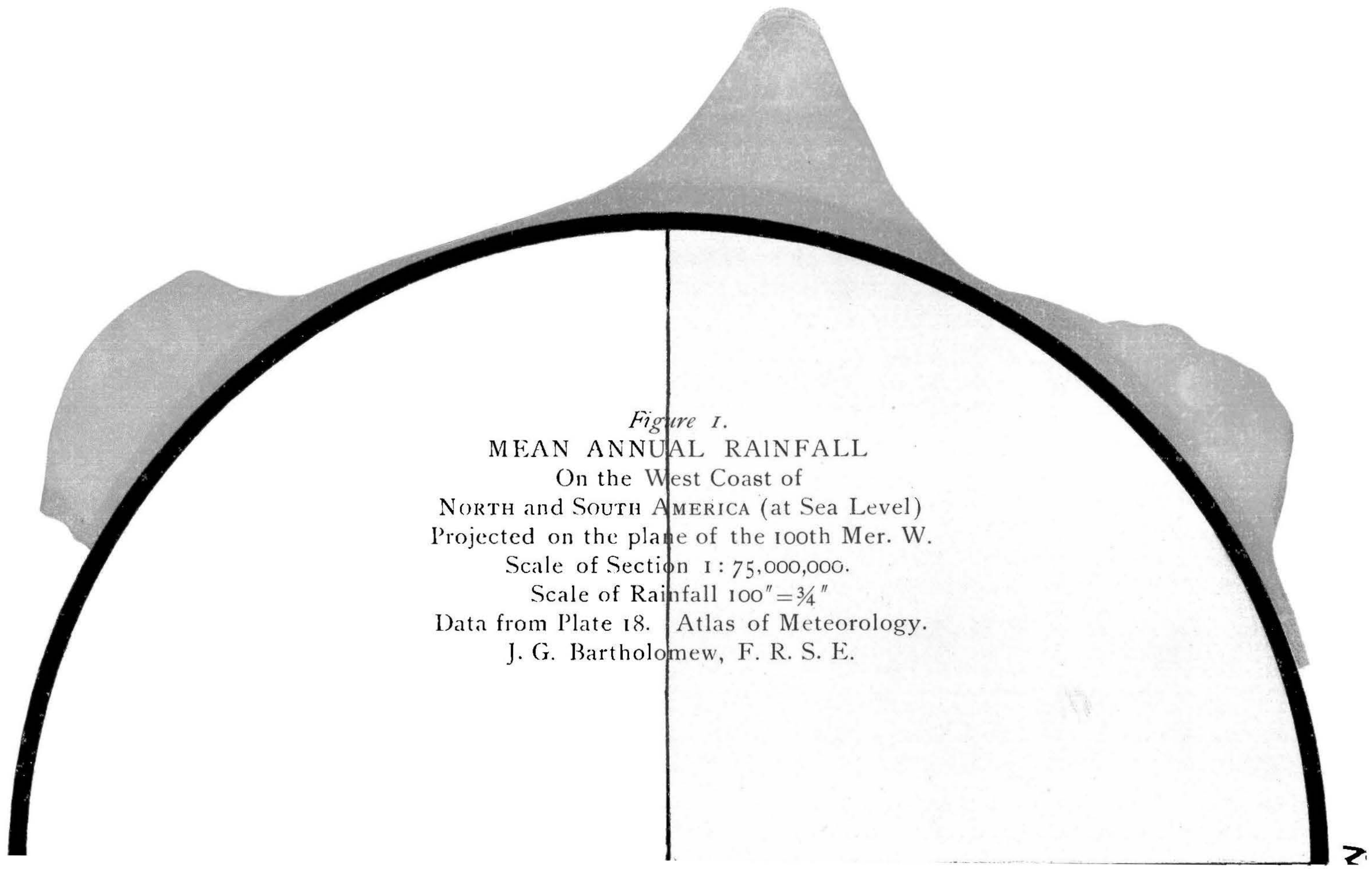

Figure 1.

MEAN ANNUAL RAINFALL

On the West Coast of

North and South America (at Sea Level)

Projected on the plane of the 100th Mer. W.

Scale of Section 1 : 75,000,000.

Scale of Rainfall 100″ = ¾″

Data from Plate 18. Atlas of Meteorology.

J. G. Bartholomew, F. R. S. E.

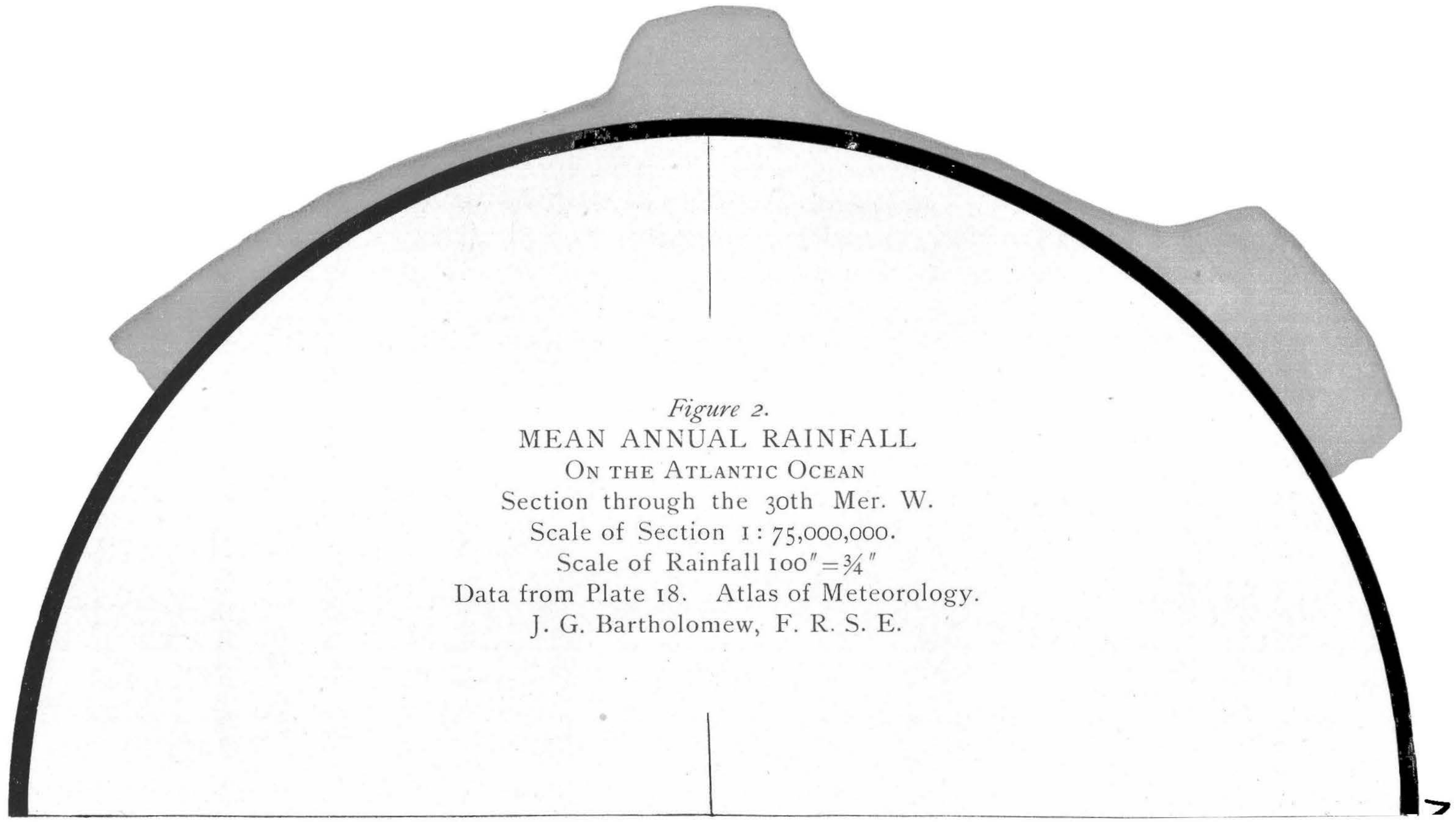

Figure 2.

MEAN ANNUAL RAINFALL

ON THE ATLANTIC OCEAN

Section through the 30th Mer. W.

Scale of Section 1 : 75,000,000.

Scale of Rainfall 100″ = ¾″

Data from Plate 18. Atlas of Meteorology.

J. G. Bartholomew, F. R. S. E.

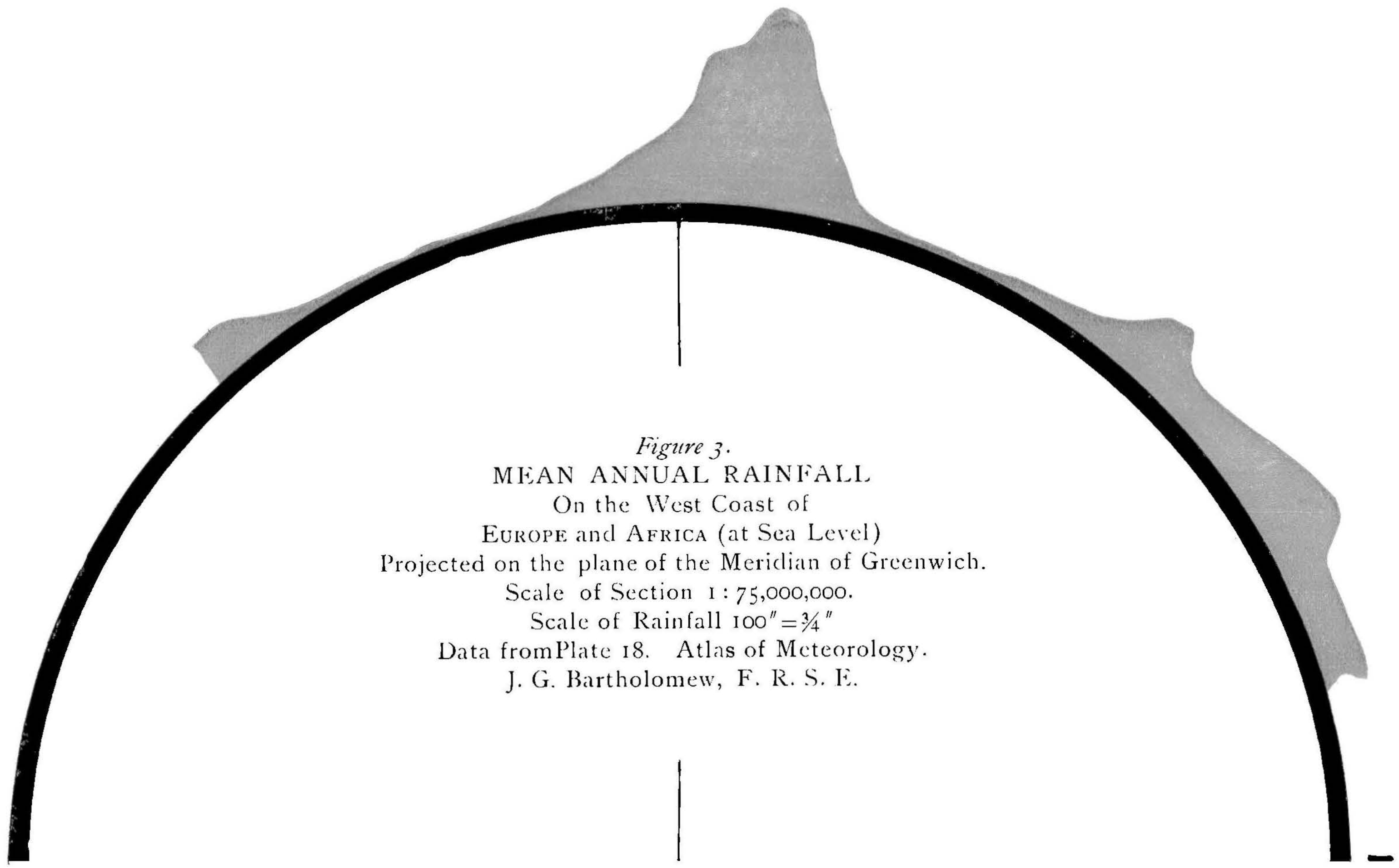

Figure 3.

MEAN ANNUAL RAINFALL

On the West Coast of

EUROPE and AFRICA (at Sea Level)

Projected on the plane of the Meridian of Greenwich.

Scale of Section 1 : 75,000,000.

Scale of Rainfall 100″ = ¾″

Data from Plate 18. Atlas of Meteorology.

J. G. Bartholomew, F. R. S. E.

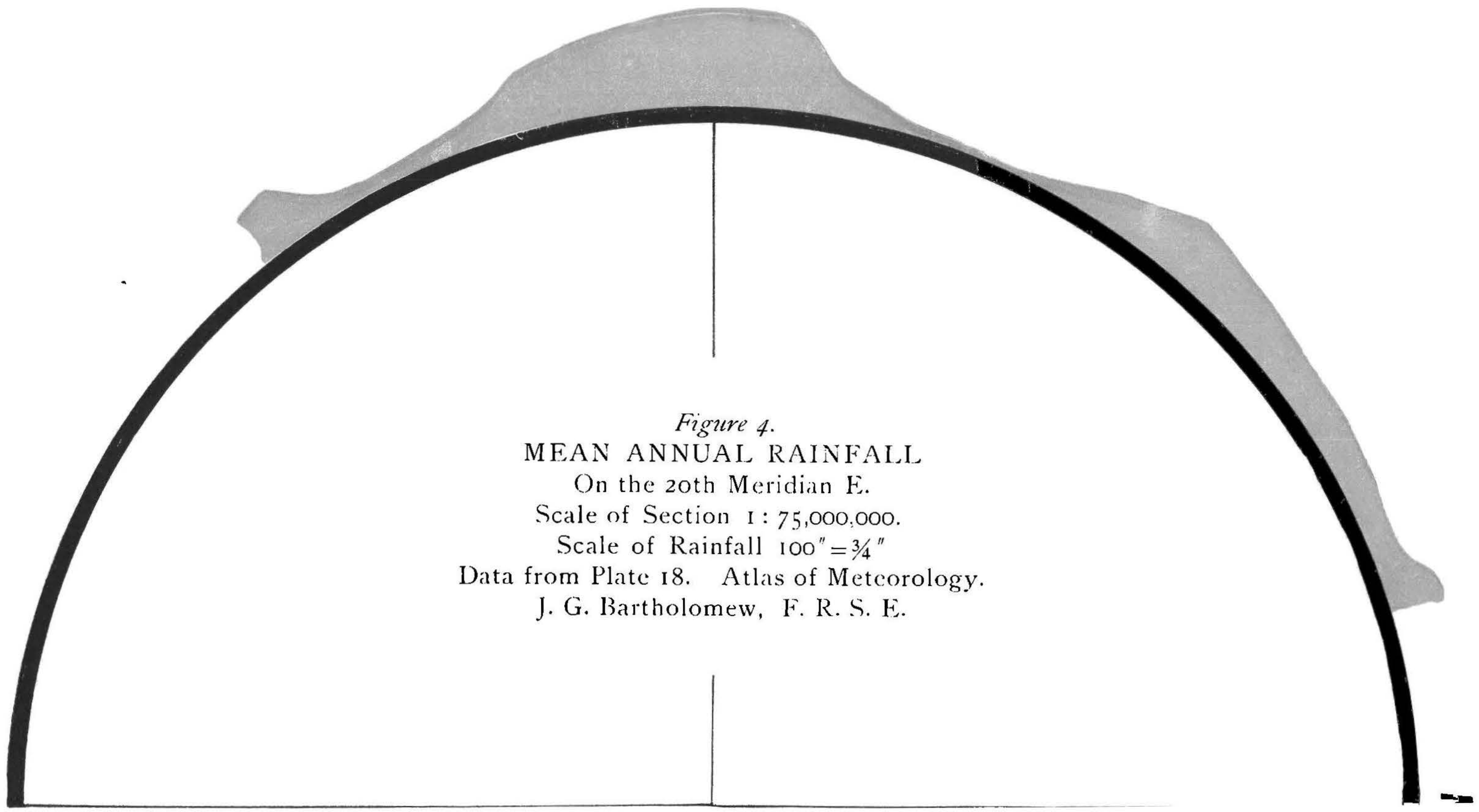

Figure 4.

MEAN ANNUAL RAINFALL

On the 20th Meridian E.

Scale of Section 1 : 75,000,000.

Scale of Rainfall 100″ = ¾″

Data from Plate 18. Atlas of Meteorology.

J. G. Bartholomew, F. R. S. E.

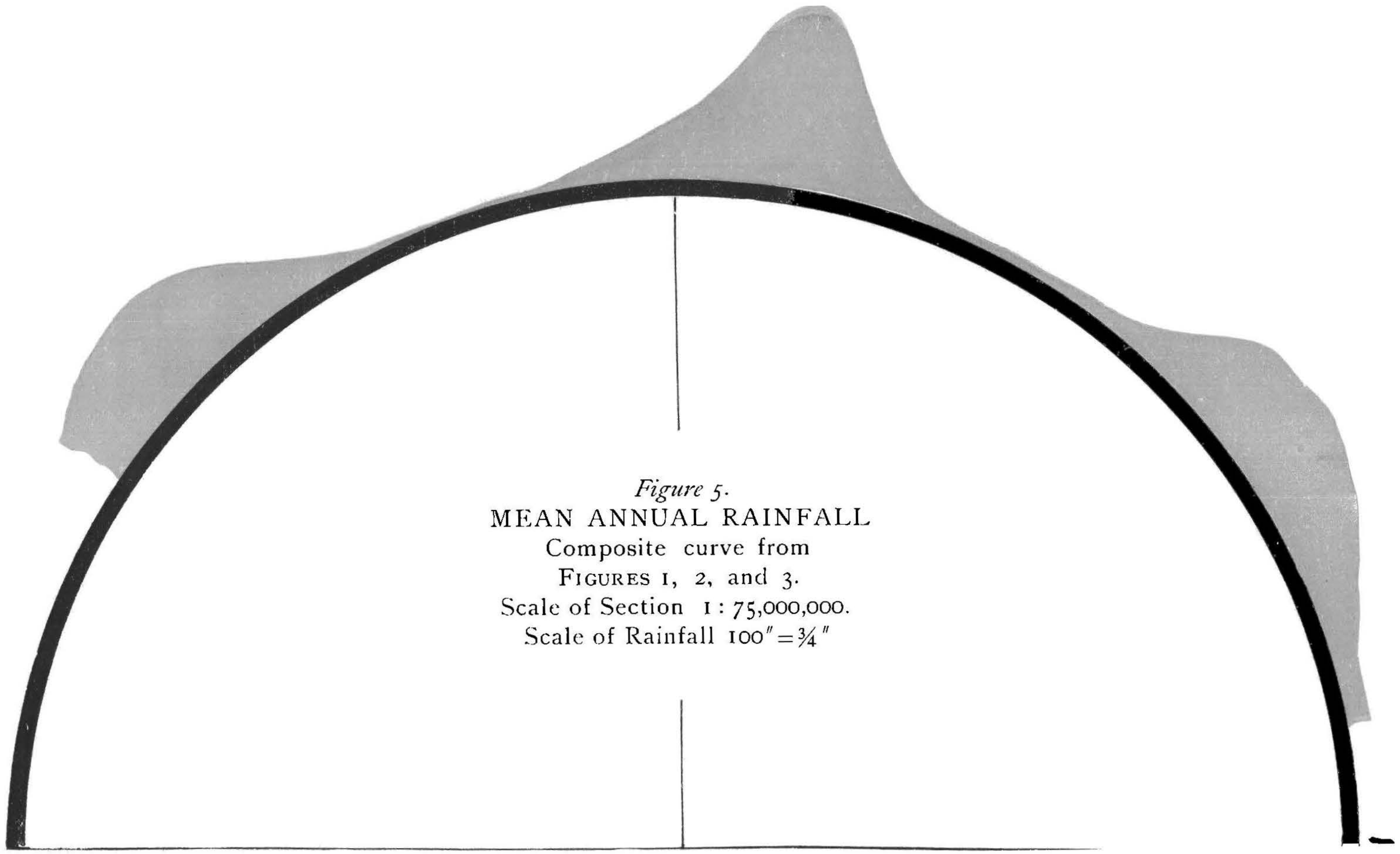

Figure 5.

MEAN ANNUAL RAINFALL

Composite curve from

FIGURES 1, 2, and 3.

Scale of Section 1 : 75,000,000.

Scale of Rainfall 100″ = ¾″

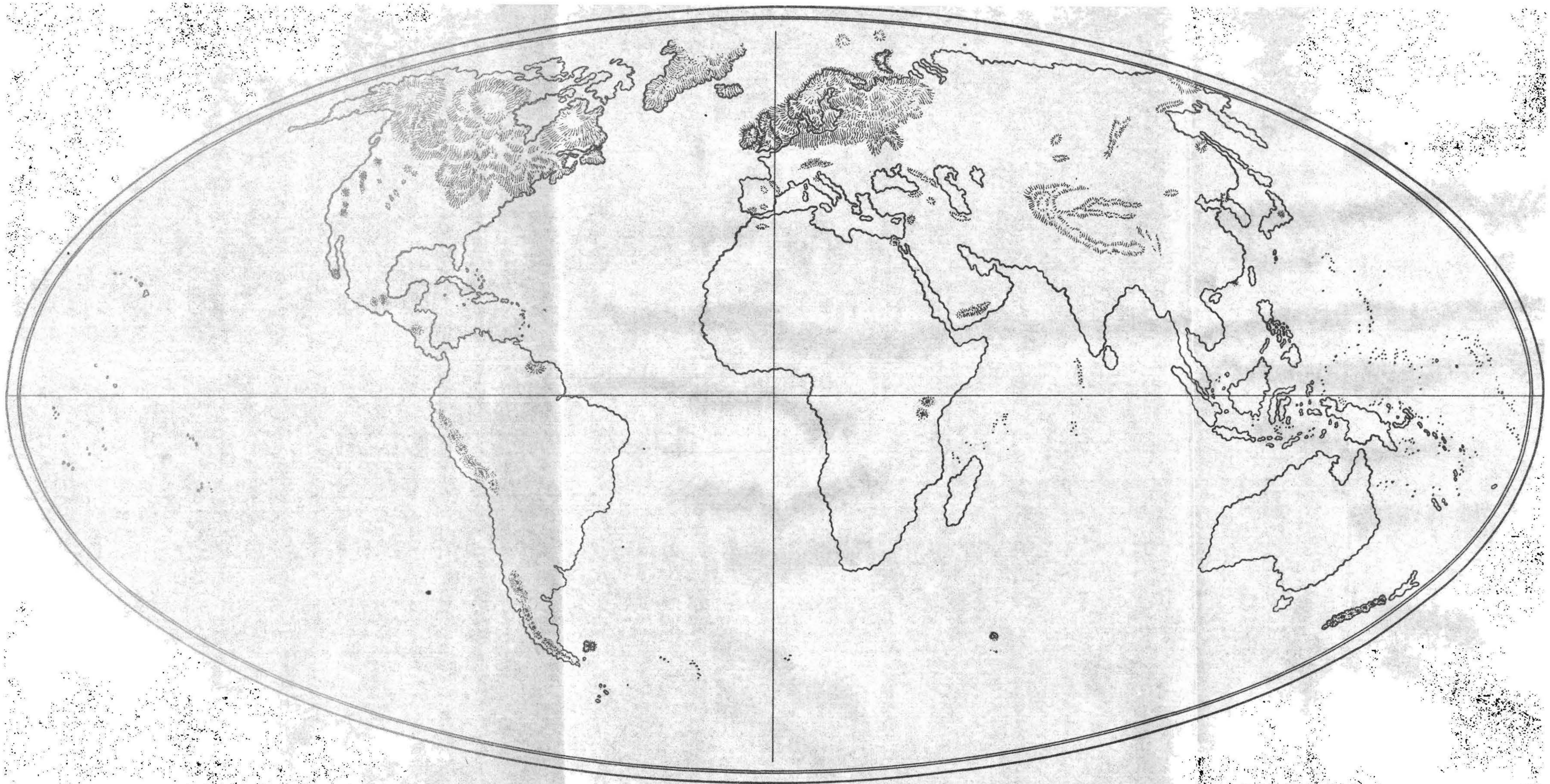

Plate A

- THE WORLD -

SHOWING

(1) THE PRESENT DISTRIBUTION OF MEAN ANNUAL RAINFALL THUS – (2) HYETAL EQUATOR THUS –·–·–·–·
(3) THE APPROXIMATE CENTER LINES OF NORTH TEMPERATE AND EQUATORIAL RAIN BELTS THUS ——— } Plate B
(4) AREAS GLACIATED DURING THE ICE AGE IN THE REGION OF THE NORTH TEMPERATE RAIN BELT THUS
(5) PRINCIPAL EXISTING GLACIERS IN TROPICAL & TEMPERATE LATITUDES SHOWING GREATER EXTENSION THUS } Plate A

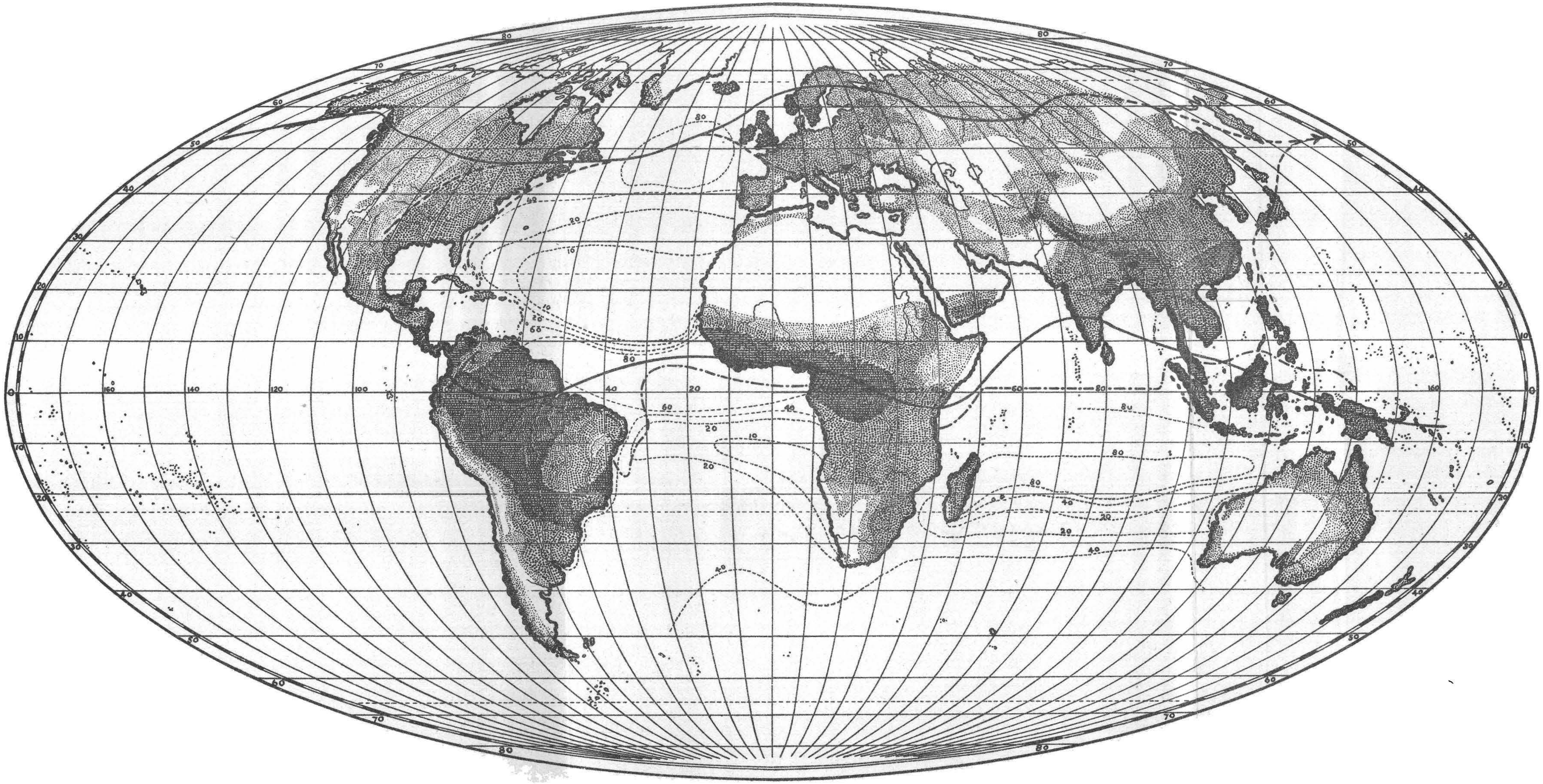

Plate B