

ART. XIV.—*On the Present Status of the Eccentricity Theory of Glacial Climate*; by W. J. MCGEE.

THE recent appearance of an important treatise, in which Croll's theory of secular variations in terrestrial climate is given a prominent place,¹ has elicited some adverse criticism of that theory, by different reviewers, which can only be regarded as embodying the current objections to the adoption of the eccentricity theory in general.

In addition to an indefinite general argument such as might equally be brought to bear against any intricate and comprehensive theory involving principles falling within the domains of diverse nascent branches of science, Gilbert² urges three definite and specific objections against the theory:

1. "If it is true, then epochs of cold must have occurred with considerable frequency through the entire period represented by the stratified rocks; and iceberg drift, if no other traces, should have been entombed at numerous horizons. It has not been found, however, and of the eight horizons claimed by Croll to show evidence of glacial action, the treatise under consideration mentions only two with confidence, and two others with doubt. In the two instances to which queries are not attached, the phenomena appear to indicate local and not general glaciation.

2. If the hypothesis is true, the cold of the Glacial epoch must have been many times interrupted by intervals of exceptional warmth; but little has been added to the evidence adduced by Croll for such an interruption, and in America, where there is now great activity in the investigation of glacial phenomena,

¹ "Text Book of Geology," A. Geikie, 1882, 21-29.

² *Nature*, xxvii, 262.

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the evidence of a *single* inter-glacial period is cumulative and overwhelming, while there is no indication whatever of more than one.

3. If the hypothesis is true, submergence in polar and temperate regions should have been coincident with glacial expansion, and emergence coincident with glacial retreat, but the Quaternary history of Great Britain, as drawn in the new textbook, includes two periods of maximum ice-extension, *separated* by a period of submergence."

The editor of the *American Naturalist*³ insists 1, that the "hypothetical stoppage of the Gulf Stream to account for the glacial climate of Northern Europe is not warranted by paleontological facts," and 2, that,—“So extremely hypothetical, from paleontological considerations, is the evidence of the so-called ‘interglacial periods,’ * * that we wonder that our author should endorse Dr. Croll’s speculations without stating some of the facts supposed to sustain such a view.”

With the conservatism characteristic of British specialists, Lapworth,⁴ in a seven-word clause, relegates the theory to the domain of “attractive speculation.”

Now these criticisms, coming as they do from the most eminent sources, and appealing as they do to indisputable facts, carry exceptional weight, and go far toward determining the future status of the theory against which they are directed; and ignoring, as they do, all of the eccentricity theory except in so far as it was originally enunciated, and is now advocated by Dr. Croll, must naturally be regarded by general students as summarily disposing of the whole subject. It is therefore most desirable that their validity should be unquestioned, that the force and bearing of the several objections should be unmistakable, and that at least the combined reviews should present fairly the status of current opinion concerning the various phases of the entire theory to which they are apparently designed to apply. To the writer these conditions do not appear to be fulfilled; and since the eccentricity theory, as now embraced by numerous students, has been specially framed to meet the difficulties urged by the reviewers, it appears to him necessary that the failure of the criticisms should be impressed upon readers of current geological literature.

So long ago as 1878, LeConte⁵ showed that if the cold of the Quaternary were the joint result of eccentricity, precession, and secular refrigeration, it may have culminated in glacial conditions but once. More recently the subject has been admirably discussed by Wallace, in a treatise which has not yet received adequate attention on this side of the Atlantic.⁶ It is there

³ xvii, 177-8.

⁴ *Geol. Mag.*, x, 80.

⁵ “*Elements of Geology*,” 1st ed., 549.

⁶ “*Island Life*,” 1881, Chs. VIII, IX.

established that, as long ago suggested by Lyell, continental configuration must exercise an important influence on the accumulation of land ice, and that the pre-Quaternary geography of the northern hemisphere was probably such as to preclude extensive ice-accumulation. In this view the recognized fundamental elements of glacial climate are eccentricity, precession and continental configuration (to which should be added, secular refrigeration). Such view has already been favorably received by LeConte,⁷ Penck⁸ and others, and no reason to question its truth has thus far appeared.

The summary objection first enumerated is therefore invalid.

The common second objection of the first two reviewers has also been anticipated by Wallace, whose climate-diagram exhibits but one a-glacial period⁹ separating two considerable glacial periods.¹⁰ The improbability that an extensive ice-sheet could be melted during an inter-glacial epoch had been previously shown, quantitatively, by the writer.¹¹ Since, however, these investigations have been alike neglected in the recent reviews, a more thorough examination must be undertaken.

While the maximum accumulation of polar ice must ever fall below that of middle latitudes,¹² and while independent glaciers may be locally developed in any latitude, provided other conditions be favorable, it may be assumed without discussion that the Quaternary ice of the northern hemisphere originated well within the arctic circle; and here, accordingly, may the manner and rate of development of an ice-sheet be considered.

Again: while glacial periods must, as is generally admitted, be periods of low temperature, and must also, as long ago demonstrated by Tyndall,¹³ be characterized by abundant precipitation, the recognition of these conditions as causative and not induced is unwarranted in the present state of knowledge; while, as best elucidated by Wallace,¹⁴ geographical vicissitudes unquestionably affect the formation of polar ice, the evidence of such changes of magnitude commensurate with the phenomena of Quaternary glaciers wholly fails; and while as urged by Croll,¹⁵ continental configuration may serve to indirectly intensify glacial conditions, its agency must ever be secondary and

⁷ "Elements of Geology," 2d ed., 1882, 578.

⁸ "Die Vergletscherung der Deutschen Alpen," 1882, 452.

⁹ Since the term "inter-glacial" was used in a definite and restricted sense by Croll, it seems desirable that some other expression should be employed to denote any considerable period, or number of periods, during which glaciers did not prevail; and for this purpose "a-glacial" is suitable.

¹⁰ "Island Life," 122.

¹¹ Geol. Mag., vi, 1879, 418.

¹² Cf. "Maximum Synchronous Glaciation," Proc. Am. Assoc. Adv. Sci., xxix, 1880, 447, *et seq.*

¹³ Cf. "Forms of Water," 1877, 154.

¹⁴ "Island Life," Ch. ix.

¹⁵ "Climate and Time," Am. ed., 1875, Ch. v; Geol. Mag., vi, 1879, 480; Geikie's Text Book, 1882, 27; and elsewhere.

subordinate. In the eccentricity theory, *per se*, then, all save the immediate effects of increased eccentricity, under conditions similar to those actually known to obtain, must be eliminated; and on these further premises may the mode and rate of ice-accumulation be sought.

In the north-frigid zone the existing ice-fields are to all appearances permanent; whence annual addition to them from congealed precipitation and loss from melting, flow of ice and water, and the liberation of bergs are practically equal. The annual precipitation can only be approximately estimated. If on the last edition of Loomis' rain chart¹⁶ the precipitation on land areas be the means of the values represented by the several tints employed, the average for the year at N. lat. 68° is 13.3 inches. Toward the pole it must be materially less: it is, indeed, sometimes so little in northern Greenland that Bessels thought the glaciers there must be but remnants of those formed during past ages.¹⁷ The mean (and the measure of melting) for the whole year certainly cannot exceed 10 inches.

Neglecting trivial amounts from diverse sources, the heat reaching the frigid zone is derived (1) from vapor-laden winds, and (2) from direct solar accession. Now that received from the first of these sources is indeterminate; but that from the second is alone sufficient to liquefy 399 inches (33.26 feet)¹⁸ annually. Actually not more (and probably far less) than $\frac{1}{40}$ of this melting can take place, and it is hence manifest that in computing the effects of eccentricity, the actual and not the theoretical values of annual addition and loss must be employed.¹⁹ The source of the discrepancy need not here be considered in detail.

For convenience, and since no appreciable error will be introduced thereby, the foregoing values for precipitation and melting, and their equality, may be assumed normal—i. e., such as would obtain were the solstices equidistant from the apsides.

Different investigators have shown that the immediate result of increased eccentricity (in conjunction with precession) must

¹⁶ This Journal, xxv, January, 1883.

¹⁷ Cited by Woeikof, "Winds of the Globe," Smithsonian Contrib. Knowl., 268, 1875 (= vol. xx, 1876), 680.

¹⁸ Cf. "Maximum Synchronous Glaciation," *op. cit.*, 473.

If, as appears from a popular notice (Harper's Magazine, lxvii, 1883, 91, cf. this Journal, xxv, 1883, 195), Langley's recent observations prove (1) that the value of solar accession hitherto accepted is too low, and (2) that the temperature of stellar space approaches absolute zero, the argument here presented will gain in force, and greater potency must be ascribed to the agencies contemplated in the eccentricity theory.

¹⁹ In the discussion already alluded to ("On the Superficial Deposits of the Mississippi Valley," Geol. Mag., vi, 1879, 418) the theoretical rate of melting was used as a basis for an estimate of the maximum removal of ice during an interglacial period; and the result is accordingly far too large.

be the inauguration of five glaciation-factors, of which two are direct and three indirect. These are, (1) diminution of mean temperature,²⁰ (2) increase of evaporation and precipitation,²¹ (3) acceleration of radiation,²² (4) promotion of reflection,²³ and (5) increase of protection from solar accession by clouds and fogs.²⁴ The first factor has been roughly evaluated only as regards its effect on temperature, whence its agency in ice-accumulation remains indefinite; and the quantitative efficiency of the last four has never been sought, and cannot now be numerically expressed without more thorough investigation than is here warranted. It must therefore suffice to assume for all a probable value;²⁵ and it will assuredly do no violence to the most conservative opinions (especially in view of the considerable influence shown to be exerted by the first factor) to assume that the united agency of the five factors is such as to counterbalance the lessened solar distance in summer, and render the combined factors effective in the sum of the excess of winter-season above normal. Manifestly, since but two (and probably not the most important) of the glaciation-factors are directly effective, while the others acquire efficiency only through the accumulation of ice, the diminution of annual melting will not be uniform but cumulative throughout the Platonic winter—the period during which winter-season occurs in aphelion; as the ice increases, so will its disposition to increase become intensified; but the assumed may be regarded as the mean rate. During each Platonic winter, then, a mean accumulation of ice directly proportional to the increase in length of winter-season will annually take place.

With the eccentricity of 210,000 years ago (0575, as computed by Croll)²⁶ the maximum excess of winter-season over the normal during such Platonic winter was about 13.5 days, or a mean for each such period of 6.75 days; throughout which period, accordingly, the annual accumulation of ice was $\frac{6.75}{365} \times 10$, or .185 inch, and within which the total accumulation was equal to $.185 \times 13,000$, or 2405 inches (200 feet).

Toward the equator actual and possible annual precipitation and liquefaction progressively increase, the first four glaciation-

²⁰ The writer, "A Contribution to Croll's Theory," this Journal, xxii, 1881, 437.

²¹ Hill, "Evaporation and Eccentricity," Geol. Mag., viii, 1881, 481; this Journal, xxiii, 1882, 61.

²² Croll, "Climate and Time," 1875, 58; Geikie's Text Book," 1882, 25.

²³ Croll, op. cit. 1, 60; op. cit. 2, 26.

²⁴ Croll, op. cit. 1, 60; op. cit. 2, 26.

²⁵ Let it be clearly understood that such an assumption is not made as an attempt to demonstrate the validity of the eccentricity theory by any process of defective reasoning; the only demonstration worthy of the name, now admissible, would be an approximate evaluation of the glaciation-factors, severally and jointly, at the various latitude of the zone over which they are efficient. Such an investigation presents no serious difficulty aside from the time and labor required in its prosecution.

²⁶ "Climate and Time," 320.

factors progressively lose in relative efficiency, the fifth increases, the share of heat derived from warmer latitudes diminishes, and the periodicity of solar accession becomes more equable, whereby loss through radiation is accelerated. From this complex of diverse and antagonistic elements only the most vague estimates of the relative rates of addition and loss in higher and lower latitudes could be directly deduced without exhaustive analysis and computation; but it is certain that the annual addition to the ice-sheet could never exceed the precipitation, while it is obvious that the annual loss must fail of the addition; whence the foregoing value, if doubled or tripled, and certainly if quadrupled, would be ample for the whole glaciated area of the northern hemisphere.

But however slow the rate of ice-accumulation, the rate of ice-dissolution, when the positions of the hemispheres were reversed, would be far slower; for the effective factors of accelerated radiation and promoted reflection, which are but secondary in the initial development of an ice-sheet, would, then reach maximum efficiency. The enormous dissipation of heat by icy surfaces is seldom adequately appreciated: after a light snow-fall equal to but a fraction of an inch of ice, in the upper Mississippi valley, the temperature falls from freezing-point to zero, and the snow is not even softened by a day's uninterrupted sunshine demonstrably sufficient to melt an inch and three-quarters of ice; the *névé*-fields of the Savoyan Alps receive enough solar energy in a year to melt 54 feet of ice, yet the actual superficial liquefaction must be trivial; an earlier paragraph indicates that less than a fortieth of the theoretical melting actually occurs in the frigid zones; the solar accession in the frigid zone in summer is considerably greater than at the equator, as Meech has calculated,²⁷ yet the liquefaction annually effected there would be effected in a week were the available energy utilized in such work; it appears susceptible of mathematic proof that if the water of the earth were converted into a mantle of ice uniformly enveloping its surface, not a crystal of it would ever be melted. Not even an approximate estimate of the rate of ice-dissolution can be made without analyzing and evaluating the wonderfully effective agencies of radiation and reflection; but it is certain again that only a fraction of the ice accumulated during a Platonic winter could be removed during a Platonic summer; and whether the fraction be large or small, it may safely be affirmed that little more than a tithe of the Quaternary ice-sheet could have been removed during a single inter-glacial period.

Let it be observed that if the preceding estimates of present

²⁷ "Relative Intensity of the Light and Heat of the Sun," *Smiths. Contrib. Knowl.*, 85, 1855 (=vol. ix, 1856), 18, pl. I.

annual precipitation, or of the combined values of the glaciation-factors, be excessive, the computed rate of ice-accumulation is too rapid; while if they be defective, the importance and efficiency of eccentricity as an element in glacial climate has been underestimated.

The foregoing results sustain the opinion of Wallace and others as already stated, and show that (presumably) the weightiest objection of the recent reviewers is invalid.

The third objection of the first reviewer is based on a subordinate side-question springing indirectly from the Crollian theory, which may or may not in any way affect the fundamental principles of the theory; for the question as to what physical effect a given mass of ice will exert on the earth's center of gravity and on the position of the ocean is wholly independent of the question as to the reason of Quaternary ice-accumulation; and the validity of the eccentricity theory, *per se*, is accordingly in no way affected by the verity of the phenomena adduced.

Again, the tripartite sequence of Quaternary deposits described in the text-book (glacial—aqueous—glacial) does not appear to be so thoroughly understood and so clearly drawn, and the consensus of opinion concerning it so uniform, as to allay the suspicion that the aqueous beds may be analogous to those everywhere deposited during and immediately after the withdrawal of the second ice-sheet.

This objection, therefore, is also invalid.

In his first objection the second reviewer overlooks the fact (upon which the writer has already had occasion to insist)²⁸ that the hypothetical deflection of the Gulf Stream, in the manner contemplated by Croll, is an *effect* of glaciation, and, if a cause at all, only a secondary one. Hence if the glaciation-factors alone are capable of inaugurating a glacial period, the assistance of this element is not essential; and if they are not alone capable of producing such an effect, the whole theory fails.

This objection, too is accordingly incompetent.

With no desire to underestimate the actual difficulties of the eccentricity theory, or to detract one iota from the laudable caution displayed in such general criticism as that of the first reviewer, a word may be added with reference to the depreciatory tone of the class of critics represented by the third reviewer. Intricate and far-reaching as the theory is, encroaching as it does upon different branches of science, involving as it must elements seldom coördinated by individual specialists, it requires for its thorough comprehension a range of preliminary study

²⁸ "Croll's 'Climate and Time'" (review), *Popular Science Monthly*, xvi, 1880, 819.

which few geologists can afford to bestow upon it; and as with special investigations generally, so in this case, the men who have not made such study are prone to ignore or disparage both the investigation and its results. It assuredly speaks strongly for the respectability, and equally makes for the probability of the theory, that nearly every geologist whose writings show that he thoroughly comprehends it is disposed to regard it as something more than a vague hypothesis, and that those who understand its principles best are most ready to teach it as a tentative but probable geologic and cosmogonic doctrine. Never more, and seldom as much, may be said of the narrower speculations of empirical geology.

Salt Lake City, Utah, April 15th, 1883.