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XII. *Examination of* Mr. Alfred R. Wallace's *Modification of the Physical Theory of Secular Changes of Climate. By* JAMES CROLL, *LL.D., F.R.S.**

ON the publication of 'Island Life,' upwards of three years ago, the author kindly favoured me with a copy. He at the same time wrote to me stating that the volume contained some modifications of my theory of secular changes of climate, to which he had been led by a careful consideration of the subject, and that he would be glad to have an expression of my opinion in regard to his results. Deeply interested as I, of course, felt in the matter, I was however compelled, owing to the state of my health, to leave the volume unread till within the last few months. This fact will account for the appearance of the following remarks at this somewhat late date.

I have read the chapters relating to Geological Climate with the greatest amount of interest and pleasure, and have to thank the author for his very clear and able exposition and defence of the main points of my theory. It appears to me, however, that what Mr. Wallace regards as modifications are in some cases really necessary parts of the theory. These may not, it is true, have been in all cases expressed by me, but they are nevertheless implied in the theory. Other points, again, regarded as modifications are simply facts lying altogether outside of the theory, which can in no way affect it. With

* Communicated by the Author.

much that Mr. Wallace has advanced in explanation of geological climate I fully agree; but I am, nevertheless, wholly unable to perceive that any of his arguments or considerations do in reality materially affect the theory advocated in 'Climate and Time.' This I hope presently to show.

Before proceeding, however, to examine in detail Mr. Wallace's modifications of the theory, it may be as well to consider one or two minor points on which I differ from him, as this will save the necessity of referring to them when we come to discuss his main argument.

Effect of Winter Solstice in Aphelion.— At page 126 ('Island Life') he says:—"We may therefore say generally, that during our northern winter, at the time of the glacial epoch, the northern hemisphere was receiving so much less heat from the sun as to lower its surface-temperature on an average about 35° F., while during the height of summer of the same period it would be receiving so much more heat as would suffice to raise its mean temperature about 60° F. above what it is now." In a footnote he adds that "the reason of the increase of summer heat being 60° while the decrease of winter cold is only 35°, is because our summer is now *below* and our winter *above* the average."

There is surely a confusion of ideas here. It is of course true that, as our summer at present occurs in aphelion and our winter in perihelion, the temperature of the former is below and that of the latter above the average; but this can afford no grounds for the result Mr. Wallace attributes to it unless it be assumed (for which there are no astronomical grounds) that our summer is 25° *further* below the average than our winter is above it.

On the Storage of Cold.—In a section on the Effects of Snow on Climate, Mr. Wallace points out the different effects produced by water falling as a liquid in the form of rain and as a solid in the form of snow. The rain, however much of it may fall, runs off rapidly, he states, without producing any permanent effect on temperature. But if snow falls, it lies where it fell, and becomes compacted into a mass which keeps the earth below and the air above, at or near the freezing-point. When the snow becomes perpetual, as on the summits of high mountains, permanent cold is the result; and however strong the sun's rays may be, the temperature of both the air and the earth cannot possibly rise much above the freezing-point. "This," he says, "is illustrated by the often-quoted fact that at 80° N. lat. Captain Scoresby had the pitch melted on the one side of his ship by the heat of the sun, while water was freezing on the other side owing to the coldness of the air."

Doubtless this is perfectly correct; but on page 502 he states that he has pointed out with more precision than has, he believes, hitherto been done, the different effects on climate of water in the liquid and solid states. This is a somewhat doubtful statement; for in chapter iv. 'Climate and Time,' in Phil. Mag. March 1870, and in other places, will, I think, be found all that this section contains. In fact the influence of snow and ice as a *permanent source of cold* is one of the main factors of my theory. The three great factors are (1) the influence of snow and ice, (2) the influence of aqueous vapour, and (3) the influence of ocean-currents. How persistently has it been urged as an objection to my theory that, during the glacial epoch, the great heat of the perihelion summer would more than counterbalance the effect of the aphelion winter. But I have maintained that the summers, notwithstanding the intensity of the sun's rays, instead of being warmer than at present, would in reality be far colder; for this reason, that the temperature of a snow-and-ice covered country can never rise much above the freezing-point. As an example of this I pointed out that, 'were it not for ice, the summers of North Greenland would be as warm as those of England (whereas in point of fact they are colder than our winters); and that were India covered with an ice-sheet, its summers would be colder than those of England.'

"Another point," he says, "of great importance in connexion with this subject is the fact, that this permanent storing-up of cold depends *entirely* on the annual amount of snowfall in proportion to that of the sun- and air-heat, and not on the actual cold of winter, or even on the average cold of the year." This, I have shown (American Journal of Science, Oct. 1883; Phil. Mag. Oct. 1883) at considerable length, is one of the most widespread and fundamental errors within the whole range of geological climatology. Perpetual snow, instead of being due "entirely" to the annual amount of snowfall in proportion to the quantity of heat received by the snow, is in most cases not even *mainly* due to this cause. Overlooking the fact that in the conservation of snow the temperature of the snow is one of the main factors has been a fruitful source of error.

High Land and Heavy Snowfall in relation to the Glacial Epoch.—According to Mr. Wallace, "high land and great moisture" are essential to the initiation of a glacial epoch. Undoubtedly high land and great moisture are the most favourable conditions for bringing about a glacial state of things; but I can hardly agree with him that they are necessary and indispensable.

As to the second of these conditions, great moisture is evidently necessary only in order to produce a great snowfall; a great snowfall is necessary only in order that the snow may become permanent; and the permanent snow in turn is necessary only in order to have permanent glaciation. But it has already been shown* that we frequently have permanent snow with a very light snowfall, even where the direct heat of the sun is excessive, as on the summits of lofty mountains. Greenland, for example, has but a very small snowfall, and yet the snow and ice are perpetual. What is necessary is, that the small amount which falls should not all melt. If this be the case, the ice will accumulate year by year, and a glacial condition will ultimately result.

Suppose that the annual precipitation of snow on a continent is equivalent to only 10 inches of ice, and that at the end of each summer one inch remains unmelted, then, in this case, the ice will continue to accumulate year by year until the quantity annually discharged by the outward motion from the centre of dispersion equals that annually formed. But in the case of a continent, this condition can be attained only when the sheet at the centre becomes of enormous thickness. Whether high land be necessary to a glacial epoch or not, it is evident that a heavy snowfall is not an indispensable condition.

As to the second of these conditions, namely High Land, it must be borne in mind that the question is not, Could the causes which are *now* in operation bring about a glacial condition of things without high land? but, Could those physical agencies brought into operation during a high state of eccentricity produce a glacial state of things without high land? Mr. Wallace's answer is that they could not. But I am not satisfied with the grounds on which he bases this opinion. A necessary condition to a glacial epoch is, of course, the existence of perpetual snow; for without perpetual snow there could be no permanent land-ice. The question then is, Could not those physical agencies brought into operation during a high state of eccentricity cover lowlands with perpetual snow without the aid of highlands? Mr. Wallace replies, "Perpetual snow nowhere exists on lowlands." Supposing this were true (I have endeavoured to show it is not†), still it does not follow that perpetual snow may not have existed on lowlands, or that, when the present condition of things changes, it may not yet exist. It is not difficult to conceive how, under

* American Journal of Science, October 1883; Philosophical Magazine, October 1883.

† Philosophical Magazine, November 1883.

certain conditions, the snow-line may in some places have been brought to the sea-level. In arctic, or even in subarctic regions, an excessively heavy snowfall, followed by piercingly cold winds from the north, during the whole of the summer months, would keep the snow at a low temperature, and certainly prevent it from disappearing. Keep the surface of the snow at or below the freezing-point, and melting will not take place, no matter how intense the sun's rays may be. A strong wind below the freezing-point will cool the surface of the snow more rapidly than the sun can manage to heat it. Another cause which would tend to keep the snow at a low temperature would be that, along with a cold northerly wind, there is usually a great diminution of aqueous vapour, thus allowing the surface of the snow to radiate its heat more freely into stellar space. For were it not for the aqueous vapour in the atmosphere, the snow-line, even at the equator, would descend to the sea-level*.

Perhaps it is owing to the warm southerly winds of the two midsummer months that Siberia, even with its inconsiderable snowfall, is not at the present day covered with permanent snow and ice. Mr. Wallace mentions that "in Siberia, within and near the Arctic circle, about six feet of snow covers the country all the winter and spring, and is not sensibly diminished by the powerful sun so long as northerly winds keep the air below the freezing-point, and occasional snow-storms occur. But early in June the wind usually changes to southerly, and under its influence the snow all disappears in a few days." But what would be the consequence were these northerly winds to continue during the whole of June and July? It would probably be that the snow of autumn would begin to fall before that of spring had disappeared. Were this to result, the country would soon become covered with permanent ice. Matters would be still worse if these southerly winds, instead of ceasing, were simply to change from June and July to December and January, for then, in place of producing a melting effect, they would greatly add to the snowfall.

Such a condition of things may never have obtained on the plains of Siberia†; but I have shown in my paper on the Ice of Greenland and the Antarctic regions‡ that there are certainly good grounds for concluding that during the glacial

* See American Journal of Science for October 1883; Philosophical Magazine for October 1883.

† Sir Joseph Dalton Hooker suggests to me that the Ice-cliffs of Siberia may, however, be relics of the Glacial Epoch.

‡ Phil. Mag. for November 1883.

epoch, and even at a date more recent, permanent ice must have begun to accumulate on lowlands, which could not have been the case had not the ground been previously covered with perpetual snow.

The only Continental Ice on the Globe probably on Lowlands.—The only two continents on the globe covered by permanent ice and snow are Greenland and the Antarctic. But are these continents to be regarded as high lands or as low lands? Mr. Wallace maintains that they are high lands. "It is," he says, "only where there are lofty mountains or elevated plateaus, as in Greenland &c., that glaciers accompanied by perpetual snow cover the country. The north polar area is free from any accumulation of permanent ice, excepting the high lands of Greenland and Grinnell Land." And in regard to the Antarctic continent he says, "The much greater quantity of ice at the south pole is undoubtedly due to the presence of a large extent of high land." Were it not for these extensive highlands and lofty mountains, Greenland and the Antarctic regions, according to Mr. Wallace's theory, would be free from permanent snow and ice. He, however, nowhere, so far as I can find, offers any proof for the conclusion that those regions possess extensive highlands, elevated plateaus, and lofty mountains sufficient to account for these icy mantles. In the paper just referred to (Phil. Mag. November 1883) I have discussed this subject at considerable length, and have arrived at conclusions diametrically the opposite of those advocated by Mr. Wallace, viz. that Greenland and probably the greater part of the Antarctic regions consist of land probably not much above sea-level, and that the mass of ice under which they are buried must be due to some other cause than elevation of the land.

Mr. Wallace's Modification of the Theory Examined.

Mr. Wallace's chief, and, I may say, only real modification of my theory is this. I give it in his own words:—

"The alternate phases of precession—causing the winter of each hemisphere to be in *aphelion* and *perihelion* each 10,500 years—would produce a complete change of climate only where a country was *partially* snow-clad; while, whenever a large area became almost *wholly* buried in snow and ice, as was certainly the case with Northern Europe during the glacial epoch, then the glacial conditions would be continued, and perhaps even intensified, when the sun approached nearest to the earth in winter, instead of there being at the time, as Mr. Croll maintains, an almost perpetual spring."—P. 503.

"When geographical conditions and eccentricity combine to

produce a severe glacial epoch, the changing phases of precession have very little, if any, effect on the character of the climate, as mild or glacial, though it may modify the seasons; but when the eccentricity becomes moderate and the resulting climate less severe, then the changing phases of precession bring about a considerable alteration and even a partial reversal of the climate."—P. 153.

Again,—"It follows that towards the equatorial limits of a glaciated country alternations of climate may occur during a period of high eccentricity, while near the pole, where the whole country is completely ice-clad, no amelioration may take place. Exactly the same thing will occur inversely with mild Arctic climates."—P. 154.

I have, on the contrary, maintained that the more severe the glacial condition of the one hemisphere, the warmer and the more equable would necessarily be that of the other; for the very same combination of causes which would tend to cool the one hemisphere would necessarily tend to warm the other. The process to a large extent consists of a transference of heat from the one hemisphere to the other. Consequently the one hemisphere could not be heated without the other being cooled, or the one cooled without the other being heated. The hotter the one, the colder the other, and the colder the one, the hotter the other. It therefore follows that the more severe the glacial conditions, the warmer and more equable must be the interglacial warm periods. But, according to Mr. Wallace, there could be no warm interglacial periods, either in temperate or polar regions, except during the commencement and towards the close of a glacial epoch.

Before, however, proceeding to examine in detail the steps by which he arrives at this modification of my theory, it will be as well that the reader should have a clear and distinct knowledge of what that theory really is, and what it professes to explain. These I shall now briefly state in the most general terms, for misapprehension in regard to the main features of the theory lie at the root of most of the objections which have been urged against it.

General Statement of the Theory.—1st. It is not professed that the theory will account for the condition of climate during *all* past geological ages. It treats mainly of the cause of Glacial Epochs; and one of its essential elements is that these epochs consist of alternate changes, to a greater or less extent, of cold and warm periods; or, in other words, that glacial epochs must consist of alternate glacial and interglacial periods. The chief, though not the sole, aim of the theory is to account for geological climate in so far as such epochs are

concerned. Although it could be satisfactorily shown, for example, and this has certainly not yet been done, that during some past geological age, such as the Miocene, the Eocene, or the Cretaceous, the climate was throughout uniformly warm or subtropical, this would not prove that the theory was wrong, unless it could at the same time be shown that the necessary conditions demanded by the theory did then exist. But instead of this supposed condition of climate during Secondary and Tertiary periods being inconsistent with my theory, the fact is, as we shall see by and by, that this theory affords the only rational explanation of such a state of things which has yet been given.

2nd. The theory is not that a high state of eccentricity will necessarily produce a glacial epoch. No misapprehension has been more widespread or more difficult to remove than this. From the very commencement I have maintained that no amount of eccentricity, however great, could produce a glacial condition of things; that the Glacial Epoch was the result, not of a high state of eccentricity, but of a combination of *Physical* Agencies, brought into operation by means of this high state *. As an example of this misapprehension, how frequently has the present condition of the planet Mars been adduced as evidence against the theory. The eccentricity of Mars's orbit is at present greater than that of the Earth's even when at its superior limit; and its southern winter solstice is not far removed from aphelion. It is therefore maintained that, if my theory of the cause of the glacial epoch be correct, the southern hemisphere of Mars ought to be under a glacial condition, and the northern enjoying a perpetual spring—and this, as is well known, is not the case. Here it is assumed that, according to the theory, eccentricity alone ought to produce a glacial epoch, irrespective of the necessary physical conditions. We know with certainty that those physical conditions which, according to the theory, were the direct cause of the glacial epoch on our globe, cannot possibly exist on the planet Mars †. Just take one example: either the properties of water on the planet Mars or the conditions of its atmosphere must be totally different from those of our earth; for were our earth removed to Mars's distance from the sun, our seas would soon become solid ice and we could have neither snow nor rain, ocean-currents, nor any of the necessary conditions for secular change of climate. This is doubtless not the present state of Mars; but the reason of this can only be that the physical and meteorological con-

* For this reason I prefer to term the theory the Physical Theory rather than the Eccentricity Theory, as it has been called by some writers.

† See 'Climate and Time,' p. 79.

ditions of the planet must be wholly different from those of the earth.

When we reflect that a very slight change in the properties of aqueous vapour, or in the condition of our atmosphere, would effectually prevent the possibility of a glacial epoch occurring on our earth, notwithstanding a high state of eccentricity, we need not wonder that the planet Mars is not in a state of glaciation. But the eccentricity of Mars, though high, is still far from its superior limit, and the planet may yet, for any thing which we know to the contrary, pass through a glacial epoch.

3rd. Another prevailing misapprehension is the supposition that the theory does not recognize the necessity for geographical conditions. In reading 'Island Life' one might be apt to suppose that one of the chief points of difference between Mr. Wallace and myself is that he regards geographical distribution of sea and land as an important factor in a theory of geological climate, whereas I entirely ignore this condition. Nothing could be further from the truth than such a supposition. I can boldly affirm that the necessity for geographical conditions is as truly a part of my theory as of Mr. Wallace's modification thereof.

One of the most important agencies, according to my view, is the enormous amount of heat conveyed from equatorial to temperate and polar regions by means of ocean-currents, and the deflection of this heat, during a high state of eccentricity, from the one hemisphere to the other. But all this depends on ocean-currents flowing from equatorial to polar regions; and the existence of these currents in turn depends, to a large extent, on the contour of the continents and the particular distribution of sea and land. Take, as one example, the Gulf-stream, a current which played so important a part in the phenomena of the glacial epoch. A very slight change in geographical conditions, such as the opening of communication between the Gulf of Mexico and the Pacific, would have greatly diminished, if not entirely destroyed, that stream. Or, as I showed on a former occasion, a change in the form or contour of the north-east corner of the South-American continent would have deflected the great equatorial current, the feeder of the Gulf-stream, into the Southern Ocean and away from the Carribean Sea. One of the main causes of the extreme condition of things in North-western Europe, as well as in eastern parts of America, during the glacial epoch, was a large withdrawal of the warm waters of the Gulf-stream; and this was to a great extent due, as I stated in my very first paper on the subject*, to the position of Cape St. Roque,

* Phil. Mag. for August 1864.

which deflected the equatorial current into the Southern Ocean. That a geographical distribution of land and water permitting of the existence and deflection of those heat-bearing currents is one of the main factors in my theory is what must be obvious to every reader of 'Climate and Time.'

The difference between Mr. Wallace and myself is this:—I maintain that with the *present* distribution of land and water, without calling in the aid of any other geographical conditions than now obtain, those physical agencies detailed in 'Climate and Time' are perfectly sufficient to account for all the phenomena of the glacial epoch, including those intercalated warm periods, during which Greenland would probably be free from ice and the Arctic regions enjoying a mild climate: while Mr. Wallace, on the other hand, maintains that without assuming some *change* in the geographical conditions of our globe those physical agencies will not account for that state of things, at least in so far as the disappearance of the ice in Arctic regions is concerned.

To narrow the field of inquiry, and bring more prominently before the mind the real question at issue, I shall state the main points on which Mr. Wallace and I appear to agree.

Points of agreement.—1. Mr. Wallace agrees with me that a high state of eccentricity could never directly produce a glacial condition of climate; that the glacial epoch was the direct result, not of a high state of eccentricity, but of a combination of physical agencies brought into operation by means of this high state.

2. He agrees with me also in regard to what these physical agencies really were; for the agencies to which he refers in his 'Island Life' are almost identically those which I have advanced in 'Climate and Time' and elsewhere.

3. Mr. Wallace agrees with me in regard to the mutual reactions of the physical agents. He maintains with me that these physical agencies not only all lead to one result—the accumulation of snow and ice—but that their efficiency in bringing about this result is strengthened by their mutual reactions on one another. At pp. 137–139 he gives a variety of examples of these mutual reactions, and says that they "produce a maximum of effect which, without their aid, would be altogether unattainable."

4. As has already been shown, we both agree as to the necessity of certain geographical conditions for the production of the glacial epoch. For although that epoch was mainly brought about by the physical agencies, yet these agencies could not have produced the required effect unless the necessary geographical conditions had been supplied, these being necessary for their effective operation.

5. Mr. Wallace admits, of course, that the necessary geographical conditions existed during the glacial epoch; for, unless this had been the case, no glacial epoch could have occurred. Therefore all that was required to produce glaciation was an amount of eccentricity sufficient to set the physical agencies into operation. Be it observed, it did not require, in *addition* to the physical agencies, some changes in the geographical conditions, or some new conditions; for the geographical conditions being existent, all that was then required to bring about the glacial epoch was the operation of the physical agencies. The overlooking of this fact has led to much confusion. For example, 210,000 years ago, with winter in aphelion, "the problem to be solved," says Mr. Wallace, "is, whether the snow that fell in winter would accumulate to such an extent that it would not be melted in summer, and so go on increasing year by year till it covered the whole of Scotland, Ireland, and Wales, and much of England. Dr. Croll and Dr. Geikie answer without hesitation that it would. Sir Charles Lyell maintained that it would only do so when geographical conditions were favourable" (p. 136). Here we have a complete misapprehension of the relation between Sir Charles Lyell's views and mine; for I would certainly maintain (and, I presume, Dr. Geikie also) as emphatically as Sir Charles could do, "that it would only do so when geographical conditions were favourable." For undoubtedly, according to the theory advocated in 'Climate and Time,' no glacial epoch could result without geographical conditions suitable for the operation of the physical agencies; and this is virtually what Sir Charles maintains. The glacial epoch resulted during the last period of high eccentricity because the geographical conditions suitable for the effective operation of the physical causes then existed.

6. It is assumed in 'Climate and Time' that, with the exception of those resulting from oscillations of sea-level, afterwards to be considered, the general distribution of sea and land, and other geographical conditions, were the same during the glacial epoch as they are at present*. Consequently, in accounting for the glacial epoch I had only to consider the

* Prof. J. Geikie, however, believes that during early Postglacial times a considerable change in the physical geography of the North seas took place (see 'Prehistoric Europe,' chap. xxi.). In order to account for the floras of Greenland, Iceland, and the Faröe Islands, he thinks a land connexion must have existed between these places and Scandinavia. For reasons which will be stated on a future occasion I am somewhat doubtful on this point. There is, I think, an important agent overlooked in the question of the distribution of Arctic flora and fauna. Prof. Geikie, however, does not believe that the climatic condition of that period was in any way due to this change.

effects resulting from those physical agencies called into operation by an increase of eccentricity. To have speculated on hypothetical geographical conditions different from those which now obtain, and on the influence which these may have had in bringing about the glacial epoch, would have been on my part perfectly absurd, as I knew we had no evidence of the existence of any such conditions. Besides, my aim was to account for that epoch from known and established facts and principles without the introduction of hypothetical causes. I fear that the fact of my making little or no allusion to geographical conditions in my explanations may have unfortunately led Mr. Wallace and others to conclude that I altogether ignore, or, at least, undervalue their importance, which is certainly not the case.

Although Mr. Wallace so frequently alludes to the importance of geographical conditions, I am not sure if he believes that during the glacial epoch those conditions differed materially from what they are at present, or that glaciation could have been greatly influenced by any difference which did exist.

7. Mr. Wallace alludes to one or two geographical conditions which, *if* they had existed during the glacial epoch, would have greatly aided glaciation; as, for example, if a land-barrier had extended from the British Isles, across the Faröe Islands and Iceland to Greenland, cutting off from Northern Europe the warm waters of the Atlantic, including the Gulf-Stream. "The result," he says, "would almost certainly be that snow would accumulate on the high mountains of Scandinavia till they became glaciated to as great an extent as Greenland."

It would be easy to multiply cases of this kind where a distribution of land and water different from the present might have been more favourable to glaciation than the present; but the question is, Did any such difference favouring glaciation *actually exist* during the glacial epoch? I have never been able to find any evidence that it did. Many a change in geographical conditions has taken place during Tertiary times, some of which were doubtless favourable to glaciation; but have we any evidence that during the glacial epoch the geographical conditions were more favourable than they are at present? Unless this can be shown to be the case, there is no necessity for referring to a difference in geographical conditions during that epoch as a cause of glaciation. This being so, it does not follow, because in my explanation of the cause of the glacial epoch I may not, like Sir Charles Lyell and others, have speculated on the effects which might

have resulted had the distribution of land and water been different from what it is now, that I ought on this account to be charged with undervaluing the importance of geographical conditions.

Mr. Wallace refers to one case of a difference in geographical conditions which he thinks might have aided glaciation. Prof. Dana has expressed the opinion that, during the height of the glacial epoch, North-eastern America was considerably elevated, bringing the wide area of the banks of Newfoundland far above water. This, Mr. Wallace thinks, would reduce the southward-flowing Arctic currents, causing the icebergs to hang about the American shores, chilling the air so as to produce constant fogs and clouds with almost perpetual snow-showers, even at midsummer. But Prof. Dana has also shown that during the glacial epoch North-eastern America was depressed as well as elevated. Now the point is, whether the elevation was contemporaneous with the cold, or with the warm periods of the glacial epoch? Mr. Wallace himself admits that depression, not elevation, of the land accompanied the increased cold; and he quotes Mr. Searles V. Wood, jun., approvingly as holding the same opinion (p. 115). It was quite natural for Prof. Dana to suppose that the elevation to which he refers occurred at the time the country was buried under ice; for when he wrote he believed the glacial epoch was chiefly due to elevation of the land caused by the lateral pressure resulting from the shrinking of the earth's crust. It is now, however, pretty well established that the continental or elevated periods of the glacial epoch, when our island was united to the mainland, were warm periods; for it was then that this country was invaded by tropical and subtropical mammalia. Had the climate at that time been cold, and the country even partially covered with snow and ice, these animals would not have made their appearance. It is therefore probable that the elevation to which Prof. Dana refers may have taken place during some of those warm periods. But be this as it may, even were it proved that during the glacial epoch geographical conditions were more favourable for the formation of ice than the present, this would not affect the general conclusion at which I wish to arrive.

Trusting that these preliminary considerations may tend to remove the partial confusion in which this somewhat complex subject has been involved, I shall now proceed to examine Mr. Wallace's main argument. I shall consider it, first, in relation to physical principles, and, secondly, in relation to geological and palæontological facts.

I. *Physics in relation to Mr. Wallace's Modification of the Theory.*

The grand modification, that during the height of the glacial epoch the snow and ice would not disappear when precession brought the winter solstice round to perihelion, I have already given in Mr. Wallace's own words. As the reasons which he assigns for this modification are very briefly stated by him, I may here give them also in his words.

After describing the state of North-eastern America and the North Atlantic, to which I have already alluded, he says :—

"But when such was the state of the North Atlantic (and, however caused, such *must* have been its state during the height of the glacial epoch), can we suppose that the mere change from the distant sun in winter and near sun in summer, to the reverse, could bring about any important alteration—*the physical and geographical causes of glaciation remaining unchanged*? For, certainly, the less powerful sun of summer, even though lasting somewhat longer, could not do more than the much more powerful sun did during the phase of summer in *perihelion*, while during the less severe winters the sun would have far less power than when it was equally near and at a very much greater altitude in summer. It seems to me, therefore, quite certain that whenever *extreme* glaciation has been brought about by high eccentricity combined with favourable geographical and physical causes (and without this combination it is doubtful whether *extreme* glaciation would ever occur), then the ice-sheet will *not* be removed during the alternate phases of precession, so long as these geographical and physical causes remain unaltered. It is true that the warm and cold oceanic currents, which are the most important agents in increasing or diminishing glaciation, depend for their strength and efficiency upon the comparative extents of the northern and southern ice-sheets; but these ice-sheets cannot, I believe, increase or diminish to any important extent unless some geographical or physical change first occurs."—P. 150.

Again,—"It is quite evident that during the height of the glacial epoch there was a combination of causes at work which led to a large portion of North-western Europe and Eastern America being buried in ice to a greater extent even than Greenland. Among these causes we must reckon a diminution of the force of the Gulf-Stream, or its being diverted from the north-western coasts of Europe; and what we have to consider is, whether the alteration from a long cold winter and short hot summer, to a short mild winter and long cool summer would greatly affect the amount of ice *if the ocean-currents remained the same.* The force of these currents is, it is true, by our hypothesis modified by the increase or diminution of the ice in the two hemispheres alternately, and they then react upon climate; but they cannot be thus changed

till after the ice-accumulation has been considerably affected by other causes."—P. 148.

There are some further reasons assigned, which will be considered as we proceed.

From what has already been shown, it will be seen that the causes which led to the glacial epoch may be classed under three distinct groups :—(1) the astronomical, (2) the physical, and (3) the geographical. This threefold division is distinctly recognized by Mr. Wallace in the above quotations, as well as in all his reasoning on the subject of geological climate.

In the astronomical group the main elements are the two following :—1st. A high state of eccentricity producing, on the hemisphere whose winter solstice happens to be in aphelion, a long and cold winter with a short and hot summer, and on the other hemisphere, whose winter solstice, of course, at the time is in perihelion, a short and mild winter with a long and cool summer: 2nd. Precession, transferring these conditions from the one hemisphere to the other alternately every 10,000 or 12,000 years. The physical elements are, of course, the influence of snow and ice, ocean-currents, aqueous vapour, clouds, fogs, and a host of other things which have already been discussed at length* ; while the geographical consist of the particular distribution of land and water, elevations or depressions in the sea-bottom, contour of the sea-coast, and other geographical conditions influencing the flow of ocean-currents.

It is to the influence of physical agencies, however, that the glacial epoch is more directly due. The main function of the astronomical agents is to set and keep the physical agencies in operation, and also to *determine* the character of their operations. For example, the position of the winter solstice in relation to the aphelion or to the perihelion, during a high state of eccentricity, determines whether the physical agencies will produce on a given hemisphere a glacial or a warm condition of climate ; while precession determines which of the two hemispheres shall be the glaciated and which the warm. In one respect we may say that the astronomical causes produce glaciation by means of the physical agencies.

The geographical conditions, however, cannot properly be considered to be causes in the sense in which the astronomical and physical are. They are more properly *conditions* to the production of a glacial epoch than *causes*. They cannot be

* 'Climate and Time,' chap. iv.; 'American Journal of Science,' Oct. 1883; Phil. Mag. Oct. 1883.

said to *act* in the production of glaciation. They are rather permanent and passive conditions enabling the active causes to produce their required effects. Had the glacial epoch resulted from elevation of the land, as some geologists suppose, then this *elevation* might properly be said to have been the cause of the glacial epoch; but the glacial epoch was produced by no such means, nor by any *change* in the physical geography of the globe. A certain geographical condition of things was, of course, requisite in order to the effective operation of the astronomical and physical causes. This condition existed at the time of the glacial epoch; and it is only in this sense that that epoch can be referred to any thing geographical.

It is true that a cause, as Sir William Hamilton states, may be defined as "all that without which the effect would not happen;" but this is far too general an expression of cause for practical purposes. We therefore fix on the particular antecedent or antecedents, through the activity of which the event is mainly brought about, and term them the causes of the event, and the others the necessary conditions.

I cannot help thinking that the way in which geographical conditions are spoken of as causes of the glacial epoch has tended to confusion.

During the glacial epoch there were frequent submergences and elevations of the land, or rather oscillations of sea-level, and these, it is true, would produce a change in the relative extent of sea and land. But whether we suppose it to have been the sea which rose and fell in relation to the land, or the land in relation to the sea, it equally follows that the geographical change resulting therefrom could not possibly have been a cause of the glacial epoch. It is now a well-established fact that submergence accompanied glaciation; the glaciation may have been that which led to the submergence; but it could not possibly have been the submergence which led to the glaciation. An elevation of the land would have favoured glaciation, but submergence would not. Its tendency would rather be in the opposite direction. It is now also established, that during the continental period, or period of elevation, the climate was warm and equable; for it was then, as has been remarked, that this country was invaded by tropical and subtropical animals. Now it is equally plain that the elevation could not have been the cause of the heat. Elevation of the land might produce cold, but it could not have been a cause of the heat. It follows therefore that the geographical change resulting from submergence or elevation of the land cannot be regarded as a cause of the glacial epoch;

for its effect on climate, if it had any, was in opposition to that of the astronomical and physical agencies. It would prove a hindrance, not a help.

Referring now to Mr. Wallace's argument: When glacial conditions in the North Atlantic attained their maximum development, "can we suppose," he asks, "that the mere change from the distant sun in winter, and near sun in summer to the reverse, could bring about any important alteration—the physical and geographical causes of glaciation remaining unchanged?" Here, to begin with, we have an impossible state of things assumed. It is assumed in this question that it is possible for the winter solstice to pass from aphelion to perihelion, and the *physical* causes to remain unchanged. It is assumed as possible that the astronomical conditions might be reversed without a reversal of the physical.

When the winter solstice is in aphelion it sets in operation many physical causes, the tendency of which is to produce an accumulation of snow and ice; but when the solstice-point moves round to the perihelion, the tendency of these causes is reversed, and they then undo what they had previously done—melt the snow and ice which they had just produced. Now, what Mr. Wallace asks is this: When, owing to the winter solstice being in aphelion during a high state of eccentricity, a glacial condition of things is produced, will the fact of the solstice-point being moved round to perihelion remove the glacial condition, if *the physical causes remain unchanged in their mode of operation*? My reply is, it certainly would not. Here it is assumed that the physical causes are working in opposition to the astronomical; that when the solstice is in perihelion the action of the physical causes, instead of being reversed, as it should be according to theory, still continues to produce and maintain a glacial state of things, the same as it did when the solstice-point was in aphelion; and he asks, will the astronomical causes in this struggle manage to overpower the physical and produce a melting of the ice? I unhesitatingly reply, no; for the physical causes are far more powerful than the astronomical. The astronomical causes, as we have seen, are perfectly unable to produce a glacial state of things without the *aid* of the physical. How, then, could we expect that they could remove this glacial state if the physical causes were actually working against them?

In thus setting the physical causes against the astronomical, Mr. Wallace is basing his argument for the nondisappearance of the snow and ice on a state of things which cannot possibly under the circumstances exist. His question, to have con-

sistency, should be this :—When glacial conditions were at their height &c., "can we suppose that the mere change from the distant sun in winter and the near sun in summer, to the reverse, could bring about any important alteration—the *geographical* causes of glaciation remaining unchanged ?" If the question is put thus, and it is the only form in which it can be put to be consistent with the theory which Mr. Wallace himself advocates, then my reply is, that the change from the distant sun in winter and near sun in summer to the near sun in winter and distant sun in summer, aided by the change in the physical causes which this would necessarily bring about, would certainly be sufficient to cause the snow and ice to disappear without any change in the geographical condition of things. The combined influence of the astronomical and physical causes, when the winter solstice is in perihelion, is perfectly sufficient to undo all that they had previously done when the solstice was in aphelion. When the action of the causes is reversed, the effects will be reversed.

Had the glacial epoch been produced by geographical causes, then it is probable that the ice would not have disappeared till these causes were changed. Had the ice, for example, been simply due to an elevation of the land, as some have argued, then it would not probably have disappeared till the land became lowered. But it was the result of no such cause. It was due, not to an elevation of the land, but to a number of physical causes, brought into operation by a high state of eccentricity. This Mr. Wallace fully admits and maintains. A certain geographical state of things was, of course, necessary to enable the astronomical and physical causes to produce the required effect ; and this was really all that geographical conditions had to do in the matter. Let this be observed, however, that the *same geographical condition of things* which favours the accumulation of ice when the winter solstice is in aphelion, favours its disappearance when the solstice is in perihelion. This is obvious, because the same combination of physical agencies which makes the hemisphere in aphelion cold, makes the one in perihelion warm. The heating of the one is, to a large extent, the result of the cooling of the other. It is the *transference* of heat by ocean-currents from the hemisphere in aphelion to the one in perihelion which is a main reason why the former is cold and the latter warm. Hence a change in geographical conditions is unnecessary for the disappearance of the ice on the hemisphere with the perihelion winter, whether that hemisphere be the northern or the southern.

The tendency of the combined influence of all the causes—

astronomical, physical, and geographical—is to cool the one hemisphere and to warm the other, to accumulate the ice on the one and remove it from the other. Consequently the same total combination of causes which will produce an accumulation of ice on either hemisphere when the winter solstice is in aphelion will produce a melting of that ice when the solstice moves round to the perihelion.

Another Impossible Condition assumed.—"What we have to consider," says Mr. Wallace, "is whether the alteration from a long cold winter and short hot summer, to a short mild winter and long cool summer, would greatly affect the amount of ice *if the ocean-currents remained the same.*" Here, again, we have an impossible state of things assumed. It is assumed that, nothwithstanding the change from an aphelion to a perihelion winter, the ocean-currents would still remain the same. And it is asked, would the astronomical causes in this case remove the glaciation? I would be disposed to say that they would not.

"The force of these currents," he adds, "are, it is true, by our hypothesis modified by the increase or diminution of the ice in the two hemispheres alternately (they depend for their strength and efficiency upon the comparative extent of the northern and southern ice-sheets), and they then react upon climate; but they cannot be thus changed till after the ice-accumulation has been considerably affected by other causes."

What, then, are the other causes which affect the ice-accumulation and thus lead to a change in the ocean-currents? "These ice-sheets cannot, I believe," says Mr. Wallace, "increase or diminish to any important extent unless some *geographical* or *physical* change first occurs." The first thing required to affect the ice-accumulation is thus a geographical or a physical change. But we have just seen that the character of the physical causes depends upon the astronomical. A change from a long cold winter and short hot summer to a short mild winter and long cool summer would reverse the operations of the physical causes and lead to a melting of the ice. The physical causes therefore offer no barrier. What more do we still require? This we have in the following footnote at page 150:—"The ocean-currents are mainly due to the difference of temperature of the polar and equatorial areas combined with the peculiar form and position of the continents, and some one or more of these factors must be altered *before* the ocean-currents towards the North Pole can be increased."

One of these factors—change in the form and position of the continents—may be left out of consideration; for we have no

evidence of any such change during the glacial epoch, except one, which, as has been already proved, could have had no effect. We must therefore look to a change in "the difference of temperature of the polar and equatorial areas" for any increase in the currents towards the north pole. And in order to bring about this change, "the only available factor," Mr. Wallace states, "is the antarctic ice; if this were largely increased, the northward-flowing currents might be so increased as to melt some of the arctic ice. But without some geographical change the antarctic ice could not materially diminish during its winter *perihelion*, nor increase to any important extent during the opposite phase. We therefore seem to have no available agency by which to get rid of the ice over a glaciated country, so long as the *geographical conditions* remained unchanged and the eccentricity continued high."

According to Mr. Wallace, the *only* available factor to produce a difference of temperature between the south-polar area and the equator, so as to increase the north-flowing currents and thus melt the arctic ice, would be an increase of the antarctic ice; but this he considers impossible without some *geographical change*. Without such a change, the antarctic ice, he maintains, would neither be increased nor diminished. Hence it follows that without this change there is, according to Mr. Wallace's theory, no possibility of getting quit of our northern ice during interglacial periods.

This sweeping conclusion seems to be based on two assumptions, both of which appear to me to be erroneous. *First*, that the "only" factor available is the antarctic ice; and, *secondly*, that the antarctic ice can neither be increased nor diminished without some geographical change.

A Geographical Change not necessary in order to remove the Antarctic Ice.—In reference to the first, that the antarctic ice is the "only" available factor, I shall presently show that there are other causes affecting the northward-flowing currents as powerfully as the antarctic ice. As to the second, that the antarctic ice can neither be increased nor diminished materially without some geographical change, this is an assumption based, no doubt, on the opinion which he holds that the antarctic ice is due to the elevated nature of that continent. Of course if this opinion be correct, then, without a lowering of the land, the ice can never disappear or be greatly changed in amount by astronomical or physical causes. But from what has already been stated in a former article * in reference to the condition of the Antarctic regions, I think it likely that

* "The Ice of Greenland and the Antarctic Continent not due to Elevation of the Land," Phil. Mag. November 1883.

they probably consist of low dismembered land or of groups of flat islands little elevated above sea-level, but all fused together by one continuous sheet of ice. In fact, it seems highly probable that a very large portion of the ice rests on a surface which is under the sea-level. Victoria Land is, of course, certainly elevated and mountainous, but the character of the Antarctic icebergs shows that this state of things must be the exception and not the rule in those regions.

If this be the case, the antarctic ice is just in the condition admitting of its being easily modified by warm currents from equatorial regions. In fact at the very present day, as Dr. Neumayer has shown, the slight southward deflections of the warm westerly drift-current caused by the projecting land-masses of Australia, Africa, and South America, cut notches in the ice. When the southern winter solstice was in perihelion during the glacial epoch, it is probable that the greater part of the ice then disappeared.

In fact this is a result which would be even still more likely to occur were the views held by Sir Joseph Dalton Hooker and some others as to the nature of the antarctic ice proved to be correct. Sir Joseph thinks that much of the Antarctic ice-sheet, thousands of feet in thickness as it is, was formed by the successive accumulations of snow year by year on pack-ice. The snowfall in the Antarctic regions he believes to be enormous both during summer and winter; and as but a very small portion of it melts, the accumulated snow is perfectly sufficient to form such a sheet. He does not consider that there is land enough in the south-polar area to supply the astounding number and gigantic size of the icebergs that infest the ocean between lat. 50° and 70°. If this theory of Sir Joseph's be correct, and immense masses of the ice are really afloat, we can easily understand how the whole might, during a southern interglacial period, be broken up, dispersed, and melted by an inflow of equatorial water.

I think, however, that the whole of that enormous sheet from which the icebergs are derived must be resting on the ground, although it is very likely, as has been shown on a former occasion *, that a very large portion of it may be on the sea-bottom. The weight of evidence seems to favour the assumption that probably the greater part of the Antarctic regions, as has just been stated, consists of low flat groups of islands separated by broad and shallow seas which have all become filled with solid ice. It is quite possible that the ice filling these seas may have originated in pack-ice, which ultimately became converted into a solid and continuous sheet by

* Phil. Mag. November 1883, p. 357.

long ages of successive snowfalls. As layer after layer, converted into ice, was being heaped upon it year by year, the mass would gradually sink till it rested on the sea-bottom *. After this it would assume all the characteristics of continental ice. In fact we have a condition of things exactly similar in the North Sea during the height of the glacial epoch (see 'Climate and Time,' p. 449).

If such be the condition of the antarctic ice, we can readily understand how it might all soon disappear under the influence which would be brought to bear upon it were the eccentricity high and the southern winter solstice in perihelion. The warm and equable conditions of climate which would then prevail, and the enormous quantity of intertropical water carried into the Southern Ocean, would soon produce a melting of the ice. Layer after layer would disappear off the surface, and as soon as the weight of the sheet became less than that of the water which it had displaced, the sheet would float. After this it would no doubt shortly break up and become dispersed.

Other Causes than Antarctic Ice affecting the Northward-flowing Currents.—If we consider the effect which the present amount of eccentricity, small as it is, has on the climatic condition of some parts of the southern hemisphere, we shall readily understand how, during the glacial epoch, the warm water of this hemisphere may have been impelled northward, even independently of the influence of the Antarctic ice. In order to show the present effect of eccentricity on climate I cannot do better than quote Mr. Wallace's own words on the subject. Referring to its effects on south temperate America, he says:—

"Those persons who still doubt the effect of winter in *aphelion* with a high degree of eccentricity in producing glaciation, should

* In this opinion I am glad to find that Sir Joseph to a certain extent concurs, for in a letter to me on the subject he says:—"I cannot doubt but that the icebergs have originated from the ice of the great southern barrier; and what I suspect is that much of this barrier-ice originated in pack-ice over very shallow bays, increased by successive snowfalls. The quantity of snow that falls in summer is enormous south of latitude 50°–60°. Certainly it fell on half the days of each summer month during the three seasons we spent in those seas, and I think in one month snow fell *every day*. There is no summer melting of snow and ice in the Antarctic as there is in the Arctic regions. It is the only region known to me where there is perpetual snow on land at sea-level."

Now if the snow which falls in the Antarctic regions at the sea-level does not all melt, but some of it remains year by year, then permanent ice formed at the sea-level, whether it be on frozen pack or on the ground, must be a necessary consequence. If this be so, it cannot be true, as Mr. Wallace affirms, that there is no permanent ice formed but on high land.

consider how the condition of south temperate America at the present day is explicable if they reject this agency. The line of perpetual snow in the southern Andes is so low as 6000 feet in the same latitude as the Pyrenees; in the latitude of the Swiss Alps, mountains only 6200 feet high produce immense glaciers which descend to the sea-level; while in the latitude of Cumberland, mountains only from 3000 to 4000 feet high have every valley filled with streams of ice descending to the sea-coast and giving off abundance of huge icebergs. Here we have exactly the condition of things to which England and Western Europe were subjected during the latter portion of the glacial epoch, when every valley in Wales, Cumberland, and Scotland had its glacier; and to what can this state of things be imputed, if not to the fact that there is now a moderate amount of eccentricity and the winter of the southern hemisphere is in *aphelion*? The mere geographical position of the southern extremity of America does not seem especially favourable to the production of such a state of glaciation. The land narrows from the tropics southwards, and terminates altogether in about the latitude of Edinburgh: the mountains are of moderate height; while during summer the sun is three millions of miles nearer, and the heat received from it is equivalent to a rise of 20° F. as compared with the same season in the northern hemisphere."—P. 142.

In a similar glacial condition are the islands of South Georgia, South Shetland, Graham Land, Enderby Land, Sandwich Land. There can be little doubt that the present extension of ice in the Antarctic regions is to a considerable extent due also to the influence of eccentricity.

Let us now glance for a moment at the influence which this state of things has at present on northward-flowing currents. One result is that the south-east trades are stronger than the north-east, and as a consequence blow over on the northern hemisphere ten or fifteen degrees beyond the equator. This has the effect, as has been shown ('Climate and Time,' chapters v. and xiii., and other places), of impelling the warm surface-water of the southern intertropical regions over on the northern hemisphere. It is possible that the greater strength of the south-east trades may to some extent be due to the preponderance of ocean on the southern hemisphere; but there can be little doubt that it is mainly the effect of eccentricity.

The result of this transference of water from the southern to the northern hemisphere is that the intertropical waters of the northern hemisphere are between three and four degrees warmer than those of the southern. Another result which follows, as has also been shown, is that the great equatorial currents are made to lie at some distance to the north of the

equator; hence when they are impelled against the American and the Asiatic continents, and become deflected northwards and southwards, the larger portion of the water goes to the north, and thus raises the temperature of the northern hemisphere. Now if all this results as a consequence from the present small amount of eccentricity, how much greater must have been the effect during the glacial epoch, when the eccentricity was more than three times its present value and the southern winter also, as now, in aphelion! All those effects which we have just been considering would then have been magnified far more than threefold.

Climatic Conditions of the two Hemispheres the Reverse 10,000 *or* 12,000 *years ago* : *Argument from.*—Ten or twelve thousand years ago, when our northern winter solstice was last in aphelion, the climatic conditions were in all probability the reverse of what they are at present. There appears to be pretty good geological evidence that such was the case. This, under the present small amount of eccentricity, shows not only to what an extent climate is affected by eccentricity, but also (and with this we are at present more particularly concerned) that its tendency is to cool the one hemisphere and warm the other, to accumulate the snow and ice on the one and melt them on the other. And this result, to a large extent, is doubtless brought about by its influence on ocean-currents.

There are good reasons for concluding, as Prof. J. Geikie has fully shown *, that at a very recent date (during the time of the formation of the 40-feet raised beach and the deposition of the Carse-clays) the climate was much colder than it is at present. The seas surrounding our Island appear to have had a lower temperature than they have at present; and our Highland valleys seem to have been occupied by local glaciers †.

The Carse-clays of Scotland are best developed in the valleys of the Tay, the Earn, and the Forth. These deposits consist of finely laminated clays and silt. "Now and again," says Prof. J. Geikie, "the deposits consist of tough tenacious brick-clay, which does not differ in appearance from similar brick-clays of glacial age." The clay is usually free from stones, but occasionally blocks of six inches or a foot in

* 'Prehistoric Europe.'

† In a paper "On the Obliquity of the Ecliptic," read before the Geological Society of Glasgow in 1867, I concluded that at the time of the deposition of the Carse-clays the mean winter temperature was probably 10° or 15° lower than at present, and the Gulf-stream considerably reduced. See also 'Climate and Time,' pp. 403–410.

diameter are found in it; and Prof. J. Geikie mentions having seen one four feet in thickness. Stones of this size in a fine laminated clay evidently indicate the presence of floating ice. But, as Prof. J. Geikie remarks, "it is rather the general character of the clays themselves than the presence of erratics which indicates colder climatic conditions. The fine tenacious brick-clays are not like the dark sludge and silt which now gather upon the estuarine bed of the Tay, but resemble and in some cases are identical in character with the laminated clays of true glacial age with Arctic shells." These Carse-clays, as he further remarks, appear in a large measure to be made up of the fine "flour of rock" derived from the grinding action of glaciers which then occupied the Highland valleys, and from which muddy waters escaped in large quantities in summer owing to the melting of the snow and ice. In short, these Carse-clays appear to coincide with the most recent period of local glaciers.

During that period some of the glaciers, as Prof. J. Geikie has shown, appear to have even reached the sea-level. For example, at the mouth of Glen Brora, in Sutherland, there is a well-marked moraine with large blocks resting upon, and apparently of the same age as, the deposits of the raised beach *. Mr. Robert Chambers also observed moraine matter resting upon the 30-feet beach at the opening of Glen Iorsa, in Arran. In many of the Highland sea-lochs, says Prof. J. Geikie, glaciers appear to have come down to the sea and calved their icebergs there. This, he thinks, is probably the reason why the 40–50-feet beach is not often well seen at the heads of such sea-lochs. The glaciers seem in many cases to have flowed on for some distance into the sea, and thus prevented the formation of a beach and cliff-line.

The greater magnitude and torrential character of the rivers of that period were no doubt due to the melting during summer of great masses of snow and ice. The presence of the large Greenland whale, found frequently in the Carse deposits, would seem to indicate a somewhat colder sea than now surrounds our island. A decrease of temperature of the sea is what would necessarily occur from a slight diminution in the volume of the Gulf-stream, arising from the greater deflection of equatorial water into the southern hemisphere.

Another circumstance deserves notice here, as it seems to indicate that the climatic conditions of the two hemispheres were at the period of the Carse-clays the reverse of what they are at present. During that period the sea stood higher in

* 'Prehistoric Europe,' p. 411.

relation to the land than it does at the present time. To this circumstance alone no great importance can be attached; but, when we consider in addition that submergence has almost invariably accompanied glaciation, we may regard it as highly probable that the submergence at the period in question was the result of a greater amount of ice on the northern hemisphere and a less amount on the southern, than now. This probability is further increased by the fact that during the growth of the ancient Forest, which immediately underlies the Carse-clays, and indicates a condition of climate even more warm and equable than the present*, the sea stood not only higher in relation to the land than it did during the time of the deposition of the Carse-clays, but somewhat higher than it does at present. The buried Forest doubtless belongs to the period 10,000 or 12,000 years prior to that of the Carse-clays†, when the winter solstice was in perihelion; and at this time, owing to a somewhat greater amount of eccentricity than at present, the quantity of ice on the southern hemisphere might be expected to be greater, and that on the northern less, than now.

Thus when the northern winters were last in aphelion there was a *rise* of sea-level, resulting doubtless from a preponderance of ice on the northern hemisphere; but when the buried Forest flourished, 10,000 or 12,000 years prior, the winters were in perihelion, and there was a *fall* of sea-level, due in all likelihood to the preponderance of ice on the southern hemisphere. But this is not all: the strata which underlie the buried Forest bear witness to another *rise* of sea-level.

These changes of climatic conditions and oscillations of sea-level, which took place during the latter part of the Postglacial period, are just what should have taken place on the supposition that they were the result of those astronomical and physical agents which we have been considering. Thus, immediately preceding the Present period we have that of the 25- and 40-feet ‡ raised beaches and the Carse deposits, which indicate that the climate was then more severe and the sea somewhat colder and standing at a higher level than at present. Now during this Recent period our northern winter

* Those who doubt the equable and warmer character of the climate of the submarine Forest-bed period should study the mass of evidence on this point given in 'Prehistoric Europe.'

† For the probable dates of the Carse-clays and the submarine Forest-beds see Appendix.

‡ At one time I thought ('Climate and Time,' p. 409) that the 40-feet beach might belong to a period 50,000 years prior to the Carse-clays; but I am now satisfied that the two beaches both belong to the period of the Carse-clays, as Prof. J. Geikie has shown.

solstice was in aphelion, and the condition of things is exactly what, according to theory, we ought to expect.

Preceding the period of the Carse-clays comes that of the buried Forest, when the climate was even more genial and equable than at the present day, the Gulf-stream larger and the sea at a lower level than now. Now during this period the winter solstice was in perihelion and the eccentricity somewhat greater than at present; and here again we have exactly that condition of things which, according to theory, we ought to expect. It would be very singular indeed were there no physical connexion between these conditions and the causes to which I have been attributing them. It would certainly be singular were all these coincidences purely accidental. These changes have all been so recent, geologically speaking, and so general and widespread in their character, that they cannot reasonably be attributed to any known geographical changes. If we admit, then, that they were the result of those astronomical and physical agents to which I have referred them, we must also admit that those agents were as efficient in producing a warm and equable climate as in producing a cold and severe one. We must further admit that, with a very small amount of eccentricity, widely marked differences of climatic conditions are brought about on the two hemispheres; that, when the winters are in perihelion, the melting of the snow and ice and the increase of the Gulf-stream and other northward-flowing currents are as necessary a result as were the formation of the snow and ice and the decrease of the Gulf-stream and those currents when the winters were in aphelion. And if this holds true in reference to recent and postglacial times, when the eccentricity was small, it must, for reasons which will presently be stated, hold true in a higher degree in reference to the glacial epoch, when the eccentricity was more than three times its present value.

The Mutual Reaction of the Physical Agents in relation to the Melting of the Ice.—When the winter solstice is in aphelion it sets in operation, according to theory, as has been shown, a host of physical causes the tendency of which is to produce an accumulation of snow and ice; but when the solstice-point moves round to perihelion the tendency of these causes is reversed, and they then undo what they had previously done—they melt the snow and ice which they had just produced. The action of the causes being reversed, the effects are reversed. But it must be observed that the greater the amount of the eccentricity, the greater will be the effect resulting from the combination of these physical agents, whether that effect be

the production of snow and ice on the cold hemisphere, or the melting of them on the warm,—whether it be their production when the winter solstice of a hemisphere is in aphelion, or their melting when that solstice is in perihelion.

We have, however, to take into account not merely the action of the physical agents, but their Mutual Reactions on one another. The effect of this mutual reaction is very striking. Not only do the physical agents, in their actions, all lead to one result, viz. an accumulation of snow and ice when the winters are in aphelion, but their efficiency in bringing about this result is actually strengthened by their mutual reactions on one another. To illustrate this effect I quote the following from a former article:—

"To begin with, we have a high state of eccentricity. This leads to long and cold winters. The cold leads to snow, and although heat is given out in the formation of the snow, yet the final result is that the snow intensifies the cold: it cools the air and leads to still more snow. The cold and snow bring a third agent into play—*fogs*, which act still in the same direction. The fogs intercept the sun's rays, this interception of the rays diminishes the melting-power of the sun, and so increases the accumulation. As the snow and ice continue to accumulate, more and more of the rays are cut off; and on the other hand, as the rays continue to be cut off, the *rate* of accumulation increases, because the quantity of snow and ice melted becomes thus annually less and less. In addition, the loss of the rays cut off by the fogs lowers the temperature of the air and leads to more snow being formed, while again the snow thus formed chills the air still more and increases the fogs. Again, during the winters of a glacial epoch, the earth would be radiating its heat into space. Had this loss of heat simply lowered the temperature, the lowering of the temperature would have tended to diminish the rate of loss; but the result is the formation of snow rather than the lowering of the temperature.

"Further, as snow and ice accumulate on the one hemisphere they diminish on the other. This increases the strength of the trade-winds on the cold hemisphere and weakens those on the warm. The effect of this is to impel the warm water of the tropics more to the warm hemisphere than to the cold. Supposing the northern hemisphere to be the cold one, then, as the snow and ice begin gradually to accumulate, the ocean-currents of that hemisphere, more particularly the Gulf-Stream, begin to decrease in volume, while those on the southern or warm hemisphere begin *pari passu* to increase. This withdrawal of heat from the northern hemisphere favours the

accumulation of snow and ice, and as the snow and ice accumulate the ocean-currents decrease. On the other hand, as the ocean-currents diminish, the snow and ice still more accumulate. Thus the two effects, in so far as the accumulation of snow and ice is concerned, mutually strengthen each other."

With all this Mr. Wallace seems fully to agree; for at pp. 137–140 ('Island Life') he gives a very clear statement of the effect of these mutual reactions in the production of glaciation, and says that were it not for them it is probable the astronomical and other causes would not in our latitudes have been sufficient to produce glaciation. In short, he concludes that these reactions "produce a maximum of effect which, without their aid, would be altogether unattainable." Mr. Wallace thus does full justice to these mutual reactions in so far as the production of glaciation is concerned; but I am convinced that he must have underestimated their importance as regards the removal of the glaciation. He, however, recognizes the fact that these mutual reactions produce an opposite effect on the warm atmosphere whose winters are in perihelion. "These agencies," he says, "are at the same time acting in a reverse way in the southern hemisphere, diminishing the supply of the moisture carried by the anti-trades, and increasing the temperature by means of more powerful southward ocean-currents; and all this again reacts on the northern hemisphere, increasing yet further the supply of moisture by the more powerful south-westerly winds, while still further lowering the temperature by the southward diversion of the Gulf-Stream."

Now if, during the glaciation of the northern hemisphere, these mutual reactions produce the opposite effect on the southern hemisphere, it is evident that they must produce this same opposite effect on the northern hemisphere when its winter solstice is in perihelion. Their effect then would be to increase the temperature and melt the ice. When the winter solstice is moving towards the aphelion, the physical agents begin to act and also to react on one another, and this action and reaction go on increasing in intensity till the solstice-point reaches the aphelion; but an exactly similar thing is going on in the other hemisphere, only the effects are the reverse. While the actions and reactions leading to an accumulation of ice are increasing in intensity, we shall suppose, on the northern hemisphere, the same increase is taking place on the southern hemisphere; but the result is a melting, not an accumulation of the ice. The same process is undoing on the southern hemisphere what it is doing on the northern. Similarly, of course, when the northern winter solstice begins

to move towards the perihelion, the mutual reactions of these physical causes will be reversed and will go on with increasing intensity till the perihelion is reached, melting the very ice which they had previously produced.

We have already seen that the greater the extent of the eccentricity, the greater is the effect resulting from the *actions* of the physical causes, whether this effect be the production of ice on the cold hemisphere, or its removal from the warm. It is evident that the same thing must necessarily hold true in regard to the mutual *reactions* of the physical causes. Consequently if the mutual actions and reactions of the physical causes, brought into operation during a high state of eccentricity, led at the glacial epoch to the great accumulation of ice when the winters were in aphelion, they must have led to an equally great melting and dispersal of that ice when precession brought the winters round to perihelion. These causes would be as efficient in the removal of the ice as they were in its production. In so far as the physical and astronomical causes were concerned, the greater the amount of ice formed during the cold periods the greater would be the amount melted during the warm interglacial periods.

Another Reason assigned why the Ice does not Melt.—Mr. Wallace assigns the following as an additional reason why the ice does not disappear during the interglacial periods when the eccentricity is high:—

"When a country is largely covered with ice, we may look upon it as possessing the accumulated or stored-up cold of a long series of preceding winters; and however much heat is poured upon it, its temperature cannot be raised above the freezing-point till that store of cold is got rid of—that is, till the ice is all melted. But the ice itself, when extensive, tends to its own preservation, even under the influence of heat; for the chilled atmosphere becomes filled with fog, and this keeps off the sun-heat, and then snow falls even during summer, and the stored-up cold does not diminish during the year. When, however, only a small portion of the surface is covered with ice, the exposed earth becomes heated by the hot sun, this warms the air, and the warm air melts the adjacent ice. It follows that, towards the equatorial limits of a glaciated country alternations of climate may occur during a period of high eccentricity, while nearer the pole, where the whole country is completely ice-clad, no amelioration may take place."—P. 154.

For the past nineteen years I have been maintaining that, when a country is covered with ice, it becomes a permanent source of cold; and however much heat may be received from

the sun, the temperature of the surface can never be raised above the freezing-point while the ice remains; and, again, that such an ice-covering tends to its own preservation, because it chills the air and increases the snowfall. In short, I have all along maintained this to have been one of the chief causes which led to the country being so deeply covered with ice. In fact, had it not been for some such conservative power in the ice, a glacial epoch resulting from the causes which I have been advocating would not have been possible. This conservative tendency certainly renders it more difficult for the physical agencies to get rid of the ice during interglacial periods; but we evidently have no grounds for assuming that it will defy their melting-powers.

I shall next consider Geological and Palæontological Facts in relation to Mr. Wallace's modification, and also his theory as to the cause of Mild Arctic Climates.

[To be continued.]

XLI. *Examination of* Mr. Alfred R. Wallace's *Modification of the Physical Theory of Secular Changes of Climate. By* James Croll, *LL.D., F.R.S.*

[Continued from p. 111.]

Part II. *Geological and Palæontological Facts in relation to Mr. Wallace's Modificaton of the Theory.*

MR. WALLACE'S chief, and indeed only real, modification of my theory, is to the effect, as I have pointed out, that the alternate phases of precession causing the winter of each hemisphere to be in aphelion and perihelion each 10,500 years would produce a complete change of climate only when a country was partially snow-clad. According to his view, when the greater part of North-western Europe was almost wholly buried under snow and ice, those glacial conditions must have continued, and perhaps have even become intensified, when the winter solstice moved round to perihelion, instead of being replaced, as I have maintained, by an almost perpetual spring. In short, Mr. Wallace's conclusion is that, during the Glacial Epoch proper, a warm and equable Interglacial Period could not have occurred.

In the preceding part of this paper I have endeavoured to show that physical principles do not warrant such a conclusion. I shall now proceed to consider what the direct testimony of Geology and Palæontology is on the subject; and I believe we shall find that the facts of Geology and

Palæontology are as much opposed to the conclusion as are the principles of Physics.

On this point I may quote the evidence of a geologist who, more than any other, has devoted special attention to all points relating to Glacial and Interglacial periods. Prof. J. Geikie, after devoting upwards of 500 pages of his 'Prehistoric Europe' to the consideration and accumulation of facts from all parts of this country and the Continent relating to Glacial and Interglacial periods, gives the following as the result of his investigations:—

"We note," he says, "as we advance from Pliocene times, how the climatic conditions of the colder epochs of the Glacial Period increase in severity until they culminate with the appearance of that great northern *mer de glace* which overwhelmed all Northern Europe, and reached as far south as the 50th parallel of latitude in Saxony. Thereafter the glacial epochs decline in importance until in the Postglacial Period they cease to return. The genial climate of Interglacial ages probably *also attained a maximum* towards the *middle* of the Pleistocene Period, and afterwards became less genial at successive stages, the temperate and equable conditions of early Postglacial times being probably the latest manifestation of the Interglacial phase." ('Prehistoric Europe,' p. 561.)

I shall now quote the same author's description of an Interglacial Period as demonstrated by its flora and fauna. The reader must, however, observe that by Pleistocene Period Professor Geikie means the so-called Glacial Period with its alternations of severe arctic climate and mild and genial conditions. See p. 544, 'Prehistoric Europe.'

"An examination," he says, "of Pleistocene organic remains leads us to conclude that strongly contrasted climatic conditions alternated during the Period. At one time an extremely equable and genial climate prevailed, allowing animals, which are now relegated to widely-separated zones, to live throughout the year in one and the same latitude. Hippopotamuses, elephants, and rhinoceroses, Irish deer, horses, oxen, and bisons then ranged from the borders of the Mediterranean as far north at least as Middle England and Northern Germany. In like manner, plants which no longer occur together—some being banished to hilly regions, while others are restricted to low grounds, and yet others have retreated to the extreme south of the Continent or to warmer regions beyond the limits of Europe—lived side by side. The fig-tree, the judas-tree, and the Canary laurel flourished in Northern France along with the sycamore, the hazel, and the willow. And we encounter in the Pleistocene deposits of various countries in

Europe the same remarkable commingling of northern and southern forms—of forms that demand a humid climate and are capable of enduring considerable cold, together with species which, while seeking moist conditions, yet could not survive the cold of our present winters. The testimony of the mammals and plants is confirmed by that of the land and freshwater mollusca—all the evidence thus conspiring to demonstrate that the climate of Pleistocene Europe was, for some time at all events, remarkably equable and somewhat humid. The summers may not indeed have been warmer than they are now; the winters, however, were certainly much more genial." ('Prehistoric Europe,' p. 540.)

This, be it observed, is a description of a condition of things which existed during an Interglacial Period belonging, not to the close, but to the very climax of the Glacial Epoch. For immediately preceding and succeeding this Period almost the whole of Northern Europe was enveloped in one continuous sheet of ice. "But if," continues Prof. J. Geikie, "the evidence of such a climate having formerly obtained be very weighty, not less convincing are the proofs, supplied by the Pleistocene deposits, of extreme conditions. Think what must have been the state of Middle and Northern Europe when Palæolithic man hunted the reindeer in Southern France, and when the arctic willow and its congeners grew at low levels in Central Europe. Reflect upon the fact that in the very same latitude in France, where at one time the Canary laurel and the fig-tree flourished, the pine, the spruce, and northern and high-alpine mosses at another time found a congenial habitat. Bear in view, also, that the land and freshwater molluscs testify in like manner to the same strongly contrasted climate. Besides those that tell of more equable and genial conditions than the present, there are species now restricted to the higher Alps and northern latitudes that formerly abounded in middle Europe, and their shells occur commingled in the same deposits with the remains of lemmings, marmots, reindeer, and other northern and mountain-loving animals." (P. 541.)

But more convincing still is another range of facts, some of which have been adduced by Mr. Wallace himself. In a section on alternations of warm and cold periods during the Glacial Epoch ('Island Life,' p. 114), he says:—

"The evidence that such was the case" (alternate warm and cold periods) "is very remarkable. The 'Till,' as we have seen, could only have been formed when the country was entirely buried under a large ice-sheet of enormous thickness, and when it must therefore have been, in all the parts so

covered, almost entirely destitute of animal and vegetable life. But in several places in Scotland fine layers of sand and gravel, with beds of peaty matter, have been found resting on 'till' and again covered by 'till.' Sometimes these intercalated beds are very thin, but in other cases they are twenty or thirty feet thick, and in them have been found remains of the extinct ox, the Irish elk, the horse, reindeer, and mammoth. Here we have evidence of two distinct periods of intense cold, and an intervening milder period sufficiently prolonged for the country to become covered with vegetation and stocked with animal life."

Let us now see to what all this leads. It has been proved beyond the possibility of a doubt that, at the time the Till was being formed which *overlies* the Scottish interglacial beds, the whole of Scotland, Scandinavia, the bed of the North Sea, and a great part of the North of England were covered with one continuous sheet of ice upwards of 2000 feet in thickness. This sheet overwhelmed the Hebrides, the Orkney and Shetland Islands, extended into Russia, filled the basin of the Baltic, overflowed Denmark and Holstein, and advanced into North Germany as far at least as Berlin. It has also been demonstrated that, at the time the Lower Till was being formed which *underlies* these interglacial beds, North-western Europe was under a still more severe state of glaciation. The ice-sheet at this time advanced further south into England, and extended into North Germany as far as Saxony. It is perfectly obvious that this sheet must have destroyed all plant and animal life in Scotland; and before the country could have become covered with vegetation and stocked with those interglacial animals, to which Mr. Wallace refers, the ice must have disappeared and the climate become mild.

Equally conclusive are the facts adduced by Mr. Wallace in reference to the interglacial beds of England. "In the east of England Mr. Skertchly," he says, "enumerates four distinct boulder clays with intervening deposits of gravels and sands. Mr. Searles V. Wood, Jun., classes the most recent (Hessle) boulder-clay as 'post-glacial,' but he admits an intervening warmer period, characterized by southern forms of mollusca and insects, after which glacial conditions again prevailed with northern types of mollusca. Elsewhere Mr. Wood says:—'Looking at the presence of such fluviatile mollusca as *Cyrena fluminalis* and *Unio littoralis*, and of such mammalia as the hippotamus and other great pachyderms, and of such a littoral Lusitanian fauna as that of the Selsea bed, where it is mixed up with the remains of some of those pachyderms, as well as of some other features, it has seemed to me that the climate of

the earlier part of the Postglacial Period in England was possibly even warmer than our present climate; and that it was succeeded by a refrigeration sufficiently severe to cause ice to form all round our coasts, and glaciers to accumulate in the valleys of the mountain districts.'" That these fauna indicate a warm and equable condition of climate is further evident from Mr. Wallace's remarks:—"The fact," he says, "of the hippopotamus having lived at 54° N. lat. in England, quite close to the time of the Glacial Epoch, is absolutely inconsistent with a mere gradual amelioration of climate from that time till the present day. The immense quantity of vegetable food which this creature requires, implies a mild and uniform climate with hardly any severe winter; and no theory that has yet been suggested renders this possible except that of alternate cold and warm periods during the Glacial Epoch itself. . . . . Thus the very existence of the hippopotamus in Yorkshire as well as in the south of England in close association with glacial conditions must be held to be a strong corroborative argument in favour of the reality of an interglacial warm period."

I trust that Mr. Wallace has not been misled by Mr. Wood's unfortunate use of the term "Postglacial" as applied to the Hessle boulder-clay. The Hessle boulder-clay as surely belongs to the Glacial Period proper as does the true Till of Scotland, which covers the Lowlands and overlies the interglacial beds of that country. It is the *moraine profonde* of the last *mer de glace* which covered the greater part of North-western Europe. The Upper Till of Scotland and the Hessle boulder-clay of England belong to the same period. This has been clearly shown by Prof. J. Geikie in his 'Great Ice-Age,' chap. xxx. (2nd edit.), and in 'Prehistoric Europe,' chap. xii., and elsewhere. The Hessle boulder-clay is, in short, a continuation of the Upper Till of Scotland.

The position of these Hessle beds to which Mr. Wallace refers, like that of the interglacial beds of Scotland, is between two boulder-clays—the Hessle and the Purple boulder-clays, both of which indicate a period of extreme glaciation: only the Purple boulder-clay period was somewhat the more severe of the two. At both periods the greater part of North-western Europe was buried under ice. We know that during the last great ice-period, which was undoubtedly the period of the Hessle boulder-clay, the ice-sheet reached in North Germany as far as Berlin; while during the period of the Purple boulder-clay it advanced to about Saxony.

The observations of Prof. Torrell, Dr. A. Penck, Prof. Credner, Prof. Berendt, Dr. Jentzsch, A. Helland, F. Wahn-

schaffe, H. Habenicht, and other geologists have shown that there are in North Germany three distinct boulder-clays—an Upper, Middle, and Lower, with two series of interglacial beds. In these interglacial beds have been found organic remains which evidently indicate a mild and genial condition of climate. The younger interglacial period (the one prior to the last great extension of the ice) in all probability corresponds to the last interglacial period of Scotland, England, and Ireland. Interglacial beds belonging to the same period have been found in Switzerland, Italy, Denmark, North America, and other places, all indicating a mild and equable condition of climate.

There is another class of facts, almost entirely overlooked, which will doubtless yet prove even more conclusively the warm character of interglacial periods. These facts will be referred to when we come to consider the question of warm polar climates.

It would be impossible within the limits of the present paper to give even the briefest outline of the recent discoveries in regard to interglacial periods. But though this were possible it would be wholly unnecessary, as the facts which have already been adduced by Mr. Wallace himself are perfectly sufficient for our present purpose.

If now it be true, as it undoubtedly is, that the Hessle boulder-clay of England belongs to the same age as the Upper Till of Scotland, and that the last warm interglacial period, when the *Cyrena fluminalis* and *Unio littoralis*, the hippopotamus, the *Elephas antiquus*, and other animals of a southern type lived in England, occurred between two glacial periods so severe as to envelop the greater part of North-western Europe in a continuous sheet of ice, then this particular interglacial period must have supervened during a high state of eccentricity, and not, as Mr. Wallace assumes, at a period subsequent to the Glacial Epoch proper, when the eccentricity had greatly diminished. This is obvious; for if the last great ice-sheet could have been produced without a high state of eccentricity, then there seems no reason why the one preceding it should not also have been produced without high eccentricity. If so, then all the previous ice-sheets may in like manner have been so produced. For the difference in magnitude between the last and penultimate ice-sheets was not so great as to warrant the supposition of any considerable difference in the amount of eccentricity at the two periods when these ice-sheets were respectively developed. In short, if the last great ice-sheet can be explained without the supposition of a high state of eccentricity, then there does not appear to be any real necessity

for any theory of eccentricity in accounting for the Glacial Epoch.

If we adopt the Physical theory of the cause of the Glacial Epoch, we are compelled to maintain that the last two great Ice-periods were the indirect results of a high state of eccentricity, and in this case we can hardly avoid the conclusion that the mild intervening period was due to the same cause. The occurrence of a mild interglacial period between the two ice-periods is directly in opposition to Mr. Wallace's view—that during a high state of eccentricity the ice would not disappear but be continued. It is in perfect harmony, however, with that which I advocate ; for during high eccentricity a mild and equable condition of climate, when the winters occur in perihelion, is as much a necessary result as a cold and glacial condition when they occur in aphelion.

The facts of Geology thus to me appear so far to be as much opposed to Mr. Wallace's modifications as are the principles of Physics.

Difficulty in detecting the Climatic Character of the earlier Interglacial Periods.—It follows according to theory that, other things being equal, the greater the amount of eccentricity the more equable and mild will the interglacial periods be. It is probable therefore that some of the earlier interglacial periods were milder and more equable than the last. It may be difficult in the present state of our knowledge to prove this conclusion by direct geological and palæontological evidence ; but, on the other hand, it is certainly impossible to disprove it by that means. The absence of deposits containing organic remains indicative of a superior mildness of climate having obtained during early interglacial periods cannot certainly be regarded as satisfactory evidence against the conclusion just referred to. When we consider the enormous pressure and destructive power of an ice-sheet some 2000 or 3000 feet in thickness grinding down the face of a country, our surprise is that so much evidence remains of even the last interglacial period. That so few relics of the flora and fauna of preceding interglacial periods have been preserved is a conclusion which we might *à priori* anticipate. This fact has been clearly pointed out by Mr. Wallace himself, who says :—" If there have been, not two only, but a series of such alternations of climate, we could not possibly expect to find more than the most slender indications of them, because each succeeding ice-sheet would necessarily grind down or otherwise destroy much of the superficial deposits left by its predecessors, while the torrents that must always have accompanied the melting of these huge masses of ice would wash away even such fragments as might have escaped the ice itself" (p. 118).

When we pass beyond the limits reached by the ice-sheets of the Glacial Epoch we may expect, of course, to find the remains of many of the plants and animals which lived during the earlier interglacial periods. But here, again, we encounter another difficulty; for we have in this case seldom any means of determining the age to which these remains belong. Unless in relation to overlying and underlying boulder-clays, there seems in many cases no way of knowing to what interglacial period they ought to be assigned; or, in fact, whether they are really interglacial or not. If the remains in question indicated a condition of climate much milder than the present, the probability is that they would be classified as preglacial. I fully agree with Prof. J. Geikie, that many of those plants and animals of a southern type which have been regarded as preglacial are in reality of interglacial age.

Objection as to the Number of Interglacial Periods.—It has been urged as an objection to the physical theory of the Glacial Epoch, that according to it there ought to have been more interglacial periods than we have direct evidence of having actually occurred. I am doubtful as to the force of this objection. I do not think that there could have been more than about five well-marked interglacial periods during the entire Glacial Epoch; three probably during the former half of the epoch, and certainly not more than two during the latter half. There would be a large interval between the two maxima of eccentricity of 100,000 and 200,000 years ago, when the alternations of climate would be comparatively moderate in extent. Besides, it is not correct to assume, as is generally done, that the interval between two consecutive interglacial periods is only 21,000 years; for the mean rate of motion of the perihelion during the Glacial Epoch was considerably less than has been assumed. It will be seen from the Table of the Longitude of the Perihelion, given in 'Climate and Time,' p. 320, that it has taken the perihelion 231,000 years to make one complete revolution. If, therefore, we assume, what of course is not certain, that the mean rate of precession during the Glacial Epoch was the same as the present, then the rate of precession to that of the perihelion's motion would, in this case, be as 9 to 1. The equinoxial point will take 25,811 years to make one revolution; but as the perihelion moves in the opposite direction, it will reduce the time taken by the point in passing from perihelion round to perihelion to 23,230 years, which will represent the mean interval between two consecutive interglacial periods. But as the motion of the perihelion was very irregular, the length of the interval between the periods would of course differ considerably.

When we consider how difficult it must be to detect in the drift covering glaciated countries even a relic of early interglacial deposits, and when moreover we remember that it is only within the past few years that geologists have begun to bestow any attention on the subject, it is certainly not surprising that direct geological evidence of so few interglacial periods has as yet been discovered. In England geologists have, however, already detected evidence of three interglacial periods with four or five ice-periods. In Germany, quite recently, two interglacial periods and three or more ice-periods have been recognized by competent observers. In Denmark there are four boulder-clays separated by intercalated beds of sand and clay. In severely glaciated Scotland, where traces of former interglacial periods can hardly be expected, there have nevertheless been found in old preglacial buried channels and other sheltered hollows three, four, and in some places five, boulder-clays, separated from one another by immense beds of sand, gravel, and clay. Some of these beds are found to be continuous for long distances. It is true that these intercalated beds have yielded few or no organic remains, but it may well be that further research will yet result in the discovery of more abundant fossils; for frequently the beds in question are too thick and too extensive to allow us to infer their subglacial origin. They do not in such respects resemble the deposits which have been accumulated by aqueous action under ice, but have all the characteristics of deposits which have been laid down in lakes and lacustrine hollows. As some have already yielded organic remains, a more extended scrutiny will probably lead to the discovery of similar fossils in those beds which are at present believed to be unfossiliferous.

Interglacial Periods less strongly marked in Temperate Regions than Glacial.—I quite agree with Mr. Wallace that the interglacial deposits never exhibit any indication of a climate whose warmth corresponded to the severity of the preceding cold. This, however, cannot be urged as an objection, for it is a result which follows as a necessary consequence from theory. It theoretically follows that the cold of the glacial periods will not only exceed in severity the heat of the interglacial, but will also be of longer duration. During the glacial periods extreme cold is the characteristic of the winters, which, owing to the presence of snow and ice, only becomes moderated, although, of course, considerably, during the summers. But, on the other hand, during interglacial periods mildness and equability of temperature rather than heat are the characteristics both of summer and winter.

That the cold of the glacial periods must have continued

longer than the warmth of the interglacial will, I think, be apparent from the following considerations. As long as a country remains permanently covered with snow and ice, the climate, as has been repeatedly shown, must continue cold, no matter what the direct heat of the sun may be. Astronomically considered the interglacial periods are, of course, of the same length as the glacial,—the mean length of which, during the Glacial Epoch, was about 11,600 years; but the cold of a glacial period would not, as we shall presently see, actually terminate at the end of the period, but would be continued on probably for centuries into the succeeding interglacial period. Suppose that during a glacial period the country is covered with a sheet of ice, which during the continuance of the period had accumulated to the thickness of 2000 or 3000 feet. All this enormous quantity of ice would have to be melted off the ground before the warmth of the interglacial period would commence. So long as a single inch of ice covered the surface of the country, the cold would continue. Ice, as we have seen, by chilling the air induces fresh snow to fall; and of course it is only when the amount of ice annually melted exceeds that being formed from the falling snow, that a diminution in the thickness of the sheet would begin to take place. A real melting of the ice, and consequent decrease in the thickness of the sheet, would probably not commence till the astronomical and physical agencies in operation during the glacial period began to act in an opposite direction. In short, it would be the favourable conditions of the interglacial period that would effectually remove the ice; and it would be then, and only then, that the warmth would begin; while, again, at the close of the period, when the first inch of ice made its appearance on the surface of the country, the interglacial condition of climate would come to an end. The time required to remove the ice does not prevent an interglacial condition of climate; it only somewhat shortens its duration.

There is another circumstance worthy of notice here. It is this: as the mild and equable character of the climate during interglacial periods resulted to a large extent from the enormous transference of equatoreal heat, and its distribution over temperate and polar regions, the difference of climatic conditions between the subtropical and the temperate and polar regions would be less marked than at present; in other words, the temperature would not differ so much with latitude as it does at present. This, as we have seen, is a conclusion which is fully borne out by geological and palæontological facts.

The question as to the probable cause of warm polar climates will next be considered.