

ART. VI.—*On the Cause of Mild Polar Climates*; by
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THERE are few facts within the domain of geology better established than that at frequent periods in the past the polar regions enjoyed a comparatively mild and equable climate, and that places now buried under permanent snow and ice were then covered with a rich and luxuriant vegetation. Various theories have been advanced to account for this remarkable state of things, such as a different distribution of sea and land; a change in the obliquity of the ecliptic, a displacement in the position of the earth's axis of rotation, and so forth. The true explanation will, I feel persuaded, be found to be the one I gave many years ago. The steps by which the results were reached were as follows:

The annual quantity of heat received from the sun at the equator is to that at the poles as 12 to 4·98, or, say as 12 to 5. This on the supposition that the same percentage of rays is cut off by the atmosphere at the equator as at the poles, which, of course, is not the case. More is cut off at the poles than at the equator, and consequently the difference in the amount of heat received at the two places is actually greater than that indicated by the ratio 12 to 5. But, assuming 12 to 5 to be the ratio, the question arose what ought to be the *difference* of temperature between the two places in question on the supposition that the temperature was due solely to the direct heat received from the sun? This was a question difficult to answer, for its answer mainly depended upon two things, regarding both of which a very considerable amount of uncertainty prevailed.

First, it was necessary to know how much of the total amount of heat received by the earth was derived from the sun and how much from the stars and other sources, or in other words, from space. Absolute zero is considered to be 461° below zero, Fahr. The temperature of the equator is about 80°. This gives 541° as the absolute temperature of the equator. Now were all the heat received by the earth derived simply from the sun, and were the temperature of each place proportionate to the amount directly received, then the absolute temperature of the poles would be $\frac{5}{12}$ of that of the equator, or 225°. This would give a difference of 316° between the temperature of the equator and that of the poles. According to Pouillet and Herschel space has a temperature of -239°, or 222° of absolute temperature. If this be the temperature of space, then only 319° of the absolute temperature of the equator are derived from the sun; consequently as the poles receive

* From the Phil. Mag. for October, 1884.

from the sun only $\frac{1}{12}$ of this amount of temperature, or 133° , this will give merely 186° as the difference which ought to exist between the equator and the poles. There is, however, good reason for believing that the temperature of space is far less than that assigned by Pouillet and Herschel—that, in fact, it is probably not far above absolute zero. Therefore by adopting so high a temperature as -239° , we make the difference between the temperature of the equator and that of the poles too small.

Second, it was necessary to know at what rate the temperature increased or decreased with a given increase or decrease in the amount of heat received. It was well known that Newton's law—that the change of temperature was directly proportionate to the change in the quantity of heat received—was far from being correct. The formula of Dulong and Petit was found to give results pretty accurate within ordinary limits of temperature. But it would not have done, in making my estimate, to take that formula, if I adopted Herschel's estimate of the temperature of space; for it would have made the difference of temperature between the equator and the poles by far too small. Newton's law, if we adopt Herschel's estimate of the temperature of space, would give results much nearer the truth; for the error of the one would, to a large extent at least, neutralize that of the other.

From such uncertain data it was, of course, impossible to arrive at results which could in any way be regarded as accurate. But it so happens that perfect accuracy of results in the present case was not essential. All that really was required was a rough estimate of what the difference of temperature between the equator and the poles ought to be. The method adopted showed pretty clearly, however, that the difference of temperature could not be less (although probably more) than 200° . But the present actual difference does not probably exceed 80° . We have no means of ascertaining with certainty what the mean annual temperature of the poles is; but as the temperature of latitude 80° N. is $4^{\circ}\cdot5$, that of the poles is probably not under 0° . If the present difference be 80° , it is then 120° less than it would be did the temperature of each place depend alone on the heat received directly from the sun. This great reduction from about 200° to 80° can, of course, be due to no other cause than to a transference of heat from the equator to the poles. The question then arose, by what means was this transference effected? There were only two agencies available—the transference must be effected either by aerial or by ocean currents. It was shown at considerable length (*Climate and Time*, pp. 27–30, and other places) that the amount of heat that can be conveyed from the equator to the poles by

means of aerial currents is trifling, and that, consequently, the transference must be referred to the currents of the ocean. It became obvious then that the influence of ocean-currents in the distribution of heat over the globe had been enormously under-estimated. In order to ascertain with greater certainty that such had been the case, I resolved on determining, if possible, in absolute measure the amount of heat actually being conveyed from the equator to temperate and polar regions by means of ocean-currents.

The only great current whose volume and temperature had been ascertained with any degree of certainty was the Gulf-stream. On computing the absolute amount of heat conveyed by that stream, it was found to be more than equal to all the heat received from the sun within 32 miles on each side of the equator. The amount of equatorial heat carried into temperate and polar regions by this stream alone is therefore equal to one-fourth of all the heat received from the sun by the North Atlantic from the tropic of Cancer up to the Arctic Circle.* Although the heating power of the Gulf-stream had long been known, yet no one had imagined that the warmth of our climate was due, to such an enormous extent, to the heat conveyed by that stream. The amount of heat received by an equatorial zone 64 miles in breadth represents, be it observed, merely the amount conveyed by one current alone. There are several other great currents some of which convey as much heat polewards as the Gulf-stream. On taking into account the influence of the whole system of oceanic circulation, it was not surprising that the difference of temperature between the equator and the poles should be reduced from 200° to 80°.

From these considerations, the real cause of former comparatively mild climates in Arctic regions became now apparent. All that was necessary to confer on, say Greenland, a condition of climate which would admit of the growth of a luxuriant vegetation was simply an increase in the amount of heat transferred from equatorial to Arctic regions by means of ocean-currents. And to effect this change of climate, no very great amount of increase was really required; for it was shown that the severity of the climate of that region was about as much due to the cooling effect of the permanent snow and ice as to an actual want of heat. An increase in the amount of warm water entering the Arctic Ocean, just sufficient to prevent the formation of permanent ice, was all that was really necessary; for were it not for the presence of ice the summers of Greenland would be as warm as those of England.

Were the whole of the warm water of the Gulf-stream at present to flow into the Arctic Ocean, it would probably

* *Climate and Time*, pp. 34. 35; *Phil. Mag.*, February, 1870.

remove the ice of Greenland. Any physical changes, such as those that have been discussed on former occasions, which would greatly increase the volume and temperature of the stream and deflect more of its waters into the Arctic Ocean would, there is little doubt, confer on the polar regions a climate suitable for plant and animal life. At present the Gulf-stream bifurcates in mid-Atlantic, one branch passing north-eastward into the Arctic regions, whilst the larger branch turns southeastward by the Azores, and after passing the Canaries re-enters the equatorial current. As the Gulf-stream, like other great currents of the ocean, follows almost exactly the path of the prevailing winds,* it bifurcates in mid-Atlantic simply because the winds blowing over it bifurcate also. Any physical change which would prevent this bifurcation of the winds and cause them to blow northeastward would probably impel the whole of the Gulf-stream waters into the Arctic seas. All this doubtless might quite well be effected without any geographical changes, although changes in the physical geography of the North Atlantic might be helpful.

These considerations regarding the influence of the Gulf-stream point to another result of an opposite character. It is this: if a large *increase* in the volume and temperature of the stream would confer on Greenland and the Arctic regions a condition of climate somewhat like that of Northwestern Europe, it is obvious, as has been shown at length on former occasions, that a large *decrease* in its temperature and volume would, on the other hand, lead to a state of things in Northwestern Europe approaching to that which now prevails in Greenland. A decrease leads to a glacial, an increase to an inter-glacial condition of things.

Sir William Thomson on Mild Arctic Climates.—In a paper read before the Geological Society of Glasgow in February, 1877, Sir William maintains also that an increase in the amount of heat conveyed by ocean-currents to the Arctic regions, combined with the effect of Clouds, Wind, and Aqueous Vapor, is perfectly sufficient to account for the warm and temperate condition of climate which is known to have prevailed in those regions during former epochs. The following quotations will show Sir William's views:—

“A thousand feet of depression would submerge the continents of Europe, Asia and America, for thousands of miles from their present northern coast-lines, and would give instead of the present land-locked, and therefore ice-bound Arctic sea, an open iceless ocean, with only a number of small steep islands to obstruct the free interchange of water between the North Pole and temperate or tropical regions. That the Arctic sea would, in such circum-

* See ‘Climate and Time,’ p. 213.

stances, be free from ice quite up to the north pole may be, I think, securely inferred from what, in the present condition of the globe, we know of ice-bound and open seas in the northern hemisphere and of the southern ocean abounding in icebergs, but probably nowhere ice-bound up to the very coast of the circumpolar Antarctic continent, except in more or less land-locked bays." . . .

"Suppose now the sea, unobstructed by land from either pole to temperate or tropical regions, to be iceless at any time, would it continue iceless during the whole of the sunless polar winter?

Yes, we may safely answer. Supposing the depth of the sea to be not less than 50 or 100 fathoms, and judging from what we know for certain of ocean currents, we may safely say that differences of specific gravity of the water produced by difference of temperature not reaching any where down to the freezing point, would cause enough of circulation of water between the polar and temperate or tropical regions to supply all the heat radiated from the water within the Arctic circle during the sunless winter, if air contributed none of it. Just think of a current of three quarters of a nautical mile per hour, or 70 miles per four days, flowing towards the pole across the Arctic circle. The area of the Arctic circle is 700 square miles for each mile of its circumference. Hence 40 fathoms deep of such a current would carry in, per twenty-four hours, a little more than water enough to cover the whole area to a depth of 1 fathom; and this, if 7.1° Cent. above the freezing point, would bring in just enough of heat to prevent freezing, if in twenty-four hours as much heat were radiated away as taken from a tenth of a fathom of ice-cold water would leave it ice at the freezing point. This is no doubt much more than the actual amount of radiation, and the supposed current is probably much less than it would be if the water were ice-cold at the pole and 7° Cent. at the Arctic circle. Hence, without any assistance from air, we find in the convection of heat by water alone, a sufficiently powerful influence to prevent any freezing up in polar regions at any time of year."—*Trans. of the Geol. Soc. of Glasgow*, 22d February, 1877.

That an amount of warm water flowing into the Arctic Ocean equal to that assumed by Sir William Thomson, along with the effects of clouds, wind, dew, and other agencies to which he refers would wholly prevent the existence of permanent ice in those regions, is a conclusion which, I think, can hardly be doubted. It is with the greatest deference that I venture to differ from so eminent a physicist; but I am unable to believe that such a transference of water from intertropical and temperate regions could be effected by the agency to which he attributes it. Certainly the amount of heat conveyed by means of a circulation resulting from difference of specific gravity, produced by difference of temperature, must be trifling when compared with that of ocean-currents produced by the impelling force of the winds. Take, for example, the case of

the Gulf-stream. If the amount of heat conveyed from inter-tropical regions into the North Atlantic by means of difference of density resulting from difference of temperature were equal to that conveyed by the Gulf-stream, it would follow, as has been proved,* that the Atlantic would be far warmer in temperate and arctic than in intertropical regions. Taking the annual quantity of heat received from the sun per unit surface at the equator as 1,000, the quantities received by the three zones would be respectively as follows:—

Equator	1000
Torrid zone	975
Temperate zone	757
Frigid zone	454

Assume, then, that as much heat is conveyed from inter-tropical regions into the Atlantic and Arctic seas by this circulation from difference of specific gravity as by the Gulf-stream, and assume also that one half of the total heat conveyed by the two systems of circulation goes to warm the Arctic Ocean, and the other half remains in temperate regions, the following would then be the relative quantities of heat possessed by the three zones:—

Atlantic in torrid zone	671
“ in temperate zone	940
“ in frigid zone	766

There is a still more formidable objection to the theory. It has been demonstrated, from the temperature-soundings made by the “Challenger” Expedition,† that the general surface of the North Atlantic must, in order to produce equilibrium, stand at a higher level than at the equator. In other words, the surface of the Atlantic is lowest at the equator, and rises with a gentle slope to well nigh the latitude of England. This curious condition of things is owing to the fact that, in consequence of the enormous quantity of warm water from inter-tropical regions which is being continually carried by the Gulf-stream into temperate regions, the mean temperature of the Atlantic water, considered from its surface to the bottom is greater, and the specific gravity less, in temperate regions than at the equator. In consequence of this difference of specific gravity, the surface of the Atlantic at latitude 23° N. must stand 2 feet 3 inches above the level of the equator, and at latitude 38° N. 3 feet 3 inches above the equator. In this case it is absolutely impossible that there can be a flow in the Atlantic from the equatorial to the temperate regions resulting

* ‘Climate and Time,’ Chap. xi; Phil. Mag., March, 1874.

† ‘Climate and Time,’ pp. 220–225; Phil. Mag., September and December 1875; ‘Nature,’ November 25th, 1875.

from difference of specific gravity. If there is any motion of the water from that cause, it must, in so far as the Atlantic is concerned, be in the very opposite direction, viz: from the temperate to the equatorial regions.

All, or almost all, the heat which the Arctic seas receive from intertropical regions in the form of warm water comes from the Atlantic, and not from the Pacific; for the amount of warm water entering by Behring Strait must be comparatively small. It therefore follows from the foregoing considerations that none of that equatorial heat can be conveyed by a circulation resulting from difference of specific gravity produced by difference of temperature.

It is assumed as a condition in this theory that a submergence of the Arctic land of several hundred feet must have taken place in order to convert that land into a series of islands allowing of the free passage of water round them. But the evidence of geology, as was shown on a former occasion,* is not altogether favorable to the idea that those warm climates were in any way the result of a submergence of the polar land. Take the Miocene epoch as an example, all the way from Ireland and the Western Isles, by the Faroes, Iceland, Franz-Joseph Land, to North Greenland, the Miocene vegetation and the denuded fragmentary state of the strata point to a much wider distribution of Polar land than that which now obtains in those regions.

Mr. Alfred R. Wallace on mild Arctic Climates.—The theory that the mild climates of Arctic regions were due to an inflow of warm water from intertropical and temperate regions has also been fully adopted by Mr. Alfred R. Wallace. But, unlike Sir William Thomson, he does not attribute this transference of warm water to a circulation resulting from difference of density produced by difference of temperature, but to currents caused by the impelling force of the wind.

Mr. Wallace shares in the opinion now entertained by a vast number of geologists that during the whole of the Tertiary period the climate of the north temperate and polar regions was uniformly warm and mild, without a trace of any intervening epochs of cold. According to him there were no glacial or interglacial periods during Tertiary times. In this case he, of course, does not suppose that the inflow of warm water into Arctic regions, on which the mild condition of climate depended, was in any way due to those physical agencies which came into operation during an interglacial period. Mr. Wallace accounts for the mild Arctic climate during the Tertiary period by the supposition that at that time there were probably several channels extending from equatorial to arctic regions through the eastern

* Geol. Mag., September, 1878.

and western continents, allowing of a continuous flow of inter-tropical water into the Arctic Ocean. Mr. Wallace expresses his views on the point thus:—

“The distribution of the Eocene and Miocene formations shows that during a considerable portion of the Tertiary period an inland sea, more or less occupied by an archipelago of islands, extended across Central Europe between the Baltic and the Black and Caspian Seas, and thence by narrower channels south-eastward to the valley of the Euphrates and the Persian Gulf, thus opening a communication between the North Atlantic and the Indian Ocean. From the Caspian also a wide arm of the sea extended during some part of the Tertiary epoch northwards to the Arctic Ocean; and there is nothing to show that this sea may not have been in existence during the whole Tertiary period. Another channel probably existed over Egypt into the eastern basin of the Mediterranean and the Black Sea; while it is probable that there was a communication between the Baltic and the White Sea, leaving Scandinavia as an extensive island. Turning to India, we find that an arm of the sea of great width and depth extended from the Bay of Bengal to the mouths of the Indus; while the enormous depression indicated by the presence of marine fossils of Eocene age at a height of 16,500 feet in Western Tibet renders it not improbable that a more direct channel across Afghanistan may have opened a communication between the West-Asiatic and Polar seas.”—(*Island Life*, p. 184.)

My acquaintance with the Tertiary formations of the globe, and with the distribution of land and water during that period, is not such as to enable me to form any opinion whatever either as to the probability or to the improbability of the existence of such channels as are assumed by Mr. Wallace. But, looking at the question from a physical point of view, it seems to me pretty evident that if such channels as he supposes existed, allowing of a continuous flow of equatorial water into the Arctic seas, it would certainly prevent the formation of permanent ice around the pole, and would doubtless confer on the arctic regions a mild and equable climate. This would be more particularly the case if, as Mr. Wallace supposes, owing to geographical conditions, far more of the equatorial water was deflected into the arctic than into the antarctic regions.

But at the same time I think it is just as evident that these channels would not neutralize the effects resulting from a high state of eccentricity. It may be quite true that the physical cause brought into operation during a high state of eccentricity might not be sufficient to reduce the quantity of warm water flowing into the Arctic Ocean to an extent that would permit of the formation of permanent ice around the pole, but

it certainly would greatly diminish the flow into the Arctic Ocean. Supposing that at the commencement of the last Glacial epoch the volume of the Gulf-stream to have been double what it is at present; this condition of things would not have prevented the operation of these physical agents which brought about the Glacial epoch, although it, no doubt, would have considerably modified the severity of the glaciation resulting from their operation. The very same thing would hold true, though perhaps in a much greater degree in reference to the channels assumed by Mr. Wallace.

If the emissive power of the sun was about the same during the Tertiary period as at present, and there is no good grounds for supposing it was otherwise, then the extra heat possessed by the northern temperate and arctic regions must have been derived either from the equatorial regions or from the southern hemisphere, or, what is more likely, from both. If so, then the temperature either of the southern hemisphere or of the intertropical regions, or both, must have been during the Tertiary period much lower than at the present day. A lowering of the temperature of the equatorial regions, resulting from this transference of heat, would tend to produce a more equable and uniform condition of climate over the whole of the northern hemisphere. As the area of the Arctic Ocean is small in comparison to that of the equatorial zone, from which the warm water was derived, the fall of temperature at the equator would be much less than the rise at the pole. Supposing there had been a rise of say 30° at the pole resulting from a fall of 10° at the equator (and this is by no means an improbable assumption), this would reduce the difference between the equator and the pole by 40° , or to half its present amount. We should then have a climatic condition pretty much resembling that which is known to have prevailed during at least considerable portions of the Tertiary period.

It is indeed very doubtful if such a climatic condition of things as that could be brought about by a high state of eccentricity with the present distribution of land and water; but, on the other hand, it is just as doubtful whether the channels of communication assumed by Mr. Wallace could have brought it about without the aid of eccentricity.

The very existence of so high a temperature on the northern hemisphere during Tertiary times may be regarded as strong presumptive proof that the geographical conditions obtaining on the southern hemisphere were most unfavorable to the flow of intertropical water into that hemisphere. This may be one of the reasons why a high state of eccentricity failed to produce a well-marked glacial epoch on the northern hemisphere, the geographical conditions preventing a transference of warm

water into the southern hemisphere sufficient to produce true glaciation on the opposite hemisphere. That the geographical conditions obtaining on the southern hemisphere during Tertiary times were probably of such a character is an opinion advanced by Mr. Wallace himself. "There are," he says, "many peculiarities in the distribution of plants and of some groups of animals in the southern hemisphere, which render it almost certain that there has sometimes been a greater extension of the antarctic lands during Tertiary times; and it is therefore not improbable that a more or less glaciated condition may have been a long-persistent feature of the southern hemisphere, due to the peculiar distribution of land and sea, which favors the production of ice-fields and glaciers." (p. 192.)

[To be continued.]