42. *The* Glacial Climate *and the* Polar Ice-cap. By Joseph John Murphy, Esq., F.G.S. (Read June 21, 1876.)

In a paper "On the Nature and Cause of the Glacial Climate," in the Journal of the Society for 1869 (p. 350), I gave my reasons for thinking that the glacial climate was not one of intense cold, but of snowy winters and cold summers, with a small range of temperature —in four words, *not Siberian but Fuegian*. I agree with Mr. Croll that a glacial epoch is one of maximum eccentricity of the earth's orbit, and that the northern and southern hemispheres, during such an epoch, are glaciated alternately. Where I differ from him is, that while he thinks the glaciated hemisphere has its *winter* in aphelion, I maintain, on the contrary, that the glaciated hemisphere is that which has its *summer* in aphelion. Mr. Croll, in his work on 'Climate and Time,' has replied to me; and I propose in this paper to supplement my former one and give a fuller exposition of my views, showing also where I think he has fallen into error.

I quote the following from 'Climate and Time' (p. 54):—

"According to the calculations of Leverrier, the superior limit of the earth's eccentricity is 0·07075. Lagrange's determination makes the superior limit 0·07641. Recently the laborious task of reinvestigating the whole subject has been undertaken by Mr. Stockwell, of the United States. He has taken into account the disturbing influence of the planet Neptune, the existence of which was not known when Leverrier's computations were made; and he finds that the eccentricity of the earth's orbit will always be included within the limits of 0 and 0·0693888."

In order not to take too high a value, and for facility of calculation where minutely accurate results as to the effect on climate are unattainable, I take the maximum eccentricity at 0·069. The following tabular statement shows the sun's mean, perihelion, and aphelion distances, at present, and at maximum eccentricity, the ratios of the same, and the ratios of heat received by the earth at each distance:—

	At present.	At maximum eccentricity.
Sun's distance in miles.		
Mean	91,400,000	91,400,000
Perihelion	89,864,000	85,093,400
Aphelion	92,936,000	97,706,600
Ratios of distance.		
Mean	1·000	1·000
Perihelion	0·983	0·931
Aphelion.....	1·017	1·069
Ratios of heat received.		
Mean	1·000	1·000
Perihelion	1·035	1·154
Aphelion	0·967	0·875

The sun's aphelion distance occurs at present near the midsummer of the northern hemisphere; so that if, as I maintain, glaciation is the result of a cold summer due to the remoteness of the sun, the glaciation has to be accounted for by the heat received by the earth at the northern midsummer being less than at present in the ratio of 0·875 to 0·967, equal to 0·905 to 1·000, or nearly a tenth part less.

The following attempt to estimate the effect of this difference on terrestrial temperatures is by the method adopted by Mr. Croll from Sir John Herschel ('Climate and Time,' p. 37).

The temperature of space is estimated by Pouillet and Sir John Herschel at − 239° Fahr. The mean temperature of the entire northern hemisphere for July is estimated by Dove ('British-Association Report, 1848) at 71°. The mean July temperature of the northern hemisphere is therefore 310° above that of space—in other words, 310° degrees warmer than it would be in the absence of the sun. If, then, the amount of solar heat received by the earth is diminished in the ratio of 0·905 to 1·000, the temperature due to the sun should be diminished in about the same ratio, or from 310° to 280°·5, say by 30 degrees.

This estimate makes, of course, not the slightest pretension to accuracy; but it is probably nearly enough true to give an idea of the scale of the effect. In one way it is much too high. There would not be time to produce the result: the remoteness of the sun when at aphelion distance would not have so great an effect on climate as if his distance were permanently increased. But on the other hand, we have every reason to believe that Herschel's and Pouillet's estimate of the temperature of space is much too high; and the greater the difference between the temperature of the earth's surface and that of space, the greater will be the effect of any variation in the sun's distance.

The hemisphere which has its summer in aphelion has its winter in perihelion; and the winter temperature will be raised by the nearness of the sun about as much as the summer temperature is lowered by his remoteness; so that the annual range of temperature will be greatly diminished, without necessarily altering the mean temperature at all. The mean annual temperature will no doubt be lowered, from causes to be stated further on; but for the present we will suppose it unchanged. If, then, the midsummer temperature is lowered by 30° and that of midwinter raised by as much, the effect on the annual range will be 60°; and this will be enough to destroy the present difference between summer and winter in all except the most extreme climates. According to Mr. Keith Johnston, jun. ('Proceedings of the Royal Society of Edinburgh,' 1868–69), there are only three regions of the earth where the range is more than 60°: these may be roughly defined as Siberia with Central Asia, part of North America with Baffin's Bay and part of Greenland, and Lapland.

In the following tabular statement I assume the eccentricity to be at its maximum, and the perihelion to occur at the midwinter of

the northern hemisphere, which under those circumstances I believe to be the glaciated one. The parallel columns describe the climates of the world at the two solstices:—

When the Earth is in Perihelion.	*When the Earth is in Aphelion.*
The northern hemisphere has a mild winter.	The northern hemisphere has a cool summer.
The equatorial region has its hot season.	The equatorial region has its cool season.
The southern hemisphere has a hot summer.	The southern hemisphere has a cold winter.

It is thus seen that the southern hemisphere will have an extreme annual range of temperature, while that of the northern is very small; and not only so, but the effect of the equatorial hot season will spread far into the northern hemisphere, making the winter of at least the lower latitudes of that hemisphere warmer than the summer. This reversal of the seasons will probably in no case extend to the pole; in the immediately circumpolar regions the summer will always be warmer than the winter; but the line of no annual range, where the temperatures of midsummer and of midwinter are the same, instead of being, as now, near the equator*, will be perhaps near the Arctic Circle. If this is the case, the eccentricity is a little too great for the maximum of glaciation. The condition most favourable to glaciation will probably be that where the line of no annual range is at or near the margin of the polar ice-cap. But if the maximum of eccentricity is too great for the maximum of glaciation, the degree of eccentricity which will produce the maximum of glaciation will be attained at some time while the eccentricity is approaching, and again while it is receding from, its maximum.

The statements in the above tabular form would probably be accepted by every one as self-evident, if they applied to a globe having its surface all land, so that the subject of climate was not complicated by the thermal effects due to evaporation, condensation, freezing, and melting; and Mr. Croll in that case would not have propounded his strange paradox, that the mean temperature of the whole earth at maximum eccentricity is higher when in aphelion than when in perihelion. The principles stated in the above table, however, are not physical, but purely astronomical; and we have now to trace their physical results.

Round the north pole there is a considerable area, including Greenland and great part of the Asiatic and American continents, where the mean temperature of the year is below the freezing-

* See the paper by Mr. Keith Johnston, jun., already referred to.

point, and where consequently the ground at some depth is always frozen. Yet so far is this frozen area from being covered with perpetual ice, that there is no continental ice on any part of Asia or America; and though the interior of Greenland is covered with a true continental ice-sheet, yet this descends to the sea only at particular places, forming glaciers resembling, in all but magnitude, those which descend into the Alpine valleys. In few if any parts of the northern hemisphere does the ordinary line of permanent snow descend to the level of the sea. The reason of this is, that the short summer is warm enough to melt away the winter's snow. So effectually is this done, that in Siberia trees grow and crops of rye are harvested over a permanently frozen subsoil.

But let us suppose, what has repeatedly occurred, that during a period of maximum eccentricity, the precession of the equinoxes gradually brings the midsummer of the northern hemisphere round until it coincides with the aphelion. The total amount of heat received from the sun at any given latitude will remain unchanged, but, as shown above, the range of temperature will be greatly lessened. Suppose that at the border of the frozen circumpolar area (that is to say, along the isothermal of 32°) the annual range of temperature is reduced to nothing, so that the temperature is always freezing, the result will be that over the frozen area the ice and snow will never melt, and a polar ice-cap will be formed.

In one way this is a little overstated; for in no region is the climate quite invariable, and even where the mean temperature of the warmest month does not rise above 32°, there will no doubt be some melting. This, however, will have no effect, except slightly to diminish the extent of the ice-cap at its margin; and it will probably be much more than counteracted by the spreading of the ice-cap, from the same causes that make a glacier descend. Moreover the ice-cap will tend to extend itself, in consequence of the effect of masses of ice in preventing the temperature in their neighbourhood from rising much above the freezing point. For this reason the accumulation of ice will depress the temperature, especially the summer temperature, along the margin of the ice-cap; and this chilling effect will be spread into lower latitudes by means of cold currents and icebergs.

The ice-cap, as Mr. Croll has elaborately shown, will, by displacing the earth's centre of gravity, draw a greater share of ocean-water to the glaciated hemisphere; and this will promote glaciation by diminishing the range of temperature; for the range is always least in oceanic climates. Meantime the non-glaciated hemisphere will have a climate of opposite character—a climate of extremes. This is partly because of the withdrawal of ocean water from it, which will increase the area of land and make the climate more continental; but chiefly because of the nearness of the sun in summer and his remoteness in winter. The instances of Siberia and North America show that such a climate may produce a vigorous forest vegetation, which appears to be injured by no severity of

winter cold; and such was probably the climate of Greenland when it was clothed with forests.

It is true that a long and cold winter will be favourable to the formation of ice, by the freezing of water. But no great accumulation of ice, like that of the glacial period, can have been due to this cause, because the freezing of water is such a slow process that the thickest ice thus formed does not approach the thickness of a moderately thick glacier.

Thus the great heat of the perihelion summer will rapidly melt away the snow which has fallen during the aphelion winter. The question of the effect of summer heat on glaciation is, practically, to what height the temperature of the hottest month is able to clear the mountains of snow. This height is the height of the snow-line; and I have shown in my former paper, by an appeal to the facts of physical geography, that this depends chiefly on the temperature of the hottest month.

Humboldt, in his 'Cosmos,' makes the interesting remark, that if the mountains of the world were high enough, we should see an upper as well as a lower limit to the region of perpetual snow. That is to say, at a very great height the snowfall would be so small that the snow would disappear by evaporation under the summer sun. It seems not unlikely that this actually took place during the perihelion summer at maximum eccentricity, when the amount of heat received by the earth in perihelion exceeded what it is now in the ratio of 1·154 to 1·035, equal to 1·115 to 1·000, or about 10 to 9.

There is one fact of physical geography, which seems at first sight to support Mr. Croll's theory that the glacial climate was due to an aphelion winter, and not, as I maintain, to an aphelion summer. In the Antarctic regions there is a glacial climate now; the entire Antarctic continent is covered with perpetual snow down to the water's edge; yet the Antarctic summer is in perihelion. Mr. Croll thinks this is the normal state of things, and in support of his theory he states (p. 77) that

"1. The mean temperature of the southern hemisphere is less than that of the northern.

"2. The winters of the southern hemisphere are colder than those of the northern.

"3. The summers, though occurring in perihelion, are also comparatively cold.

"4. The mean temperature of the whole earth is greater in June, when it is in aphelion, than in December, when it is in perihelion."

I believe it may be confidently asserted that the first two of these statements are erroneous. The mean temperatures of the two hemispheres appear to be very nearly the same: what makes the great difference in their climates is difference of range of temperature. As compared with the northern hemisphere, the range in the southern is less; the summers are cooler, and the winters warmer. The following tabular statement of the climates of the two hemispheres is from Mr. Hopkins's paper on "Changes of Climate" in the 'Quarterly Journal' of this Society, vol. viii. (p. 72):—

Lat. 20° N.		Lat. 20° S.	
Mean	75	Mean	74·5
Range	14	Range	9
Lat. 30° N.		Lat. 30° S.	
Mean	68	Mean	69
Range	20	Range	12
Lat. 40° N.		Lat. 40° S.	
Mean	54·5	Mean	53·5
Range	35	Range	9
Lat. 50° N.		Lat. 50° S. (Falkland Islands).	
Mean	39	Mean	43
Range	46	Range	18

We know nothing of the winter temperatures of the Antarctic continent; but it seems in no way improbable that there also the range is comparatively small, so that the mean temperatures are not lower than those of corresponding Arctic latitudes, though the summer temperatures no doubt are lower. From the fact that the southern summers are cooler than the northern, it follows that the mean temperature of the whole earth is lower in the southern than in the northern summer. All this is generally and satisfactorily referred to the law that maritime climates are less extreme than continental ones, in consequence of water taking longer than land to become heated and to become cooled; and the climate of the southern hemisphere is on the whole maritime, and that of the northern continental. But if the relative extent and distribution of land and sea were nearly the same in the two hemispheres, I cannot doubt that, contrary to Mr. Croll's opinion, the southern hemisphere, having a perihelion summer and an aphelion winter, would have a warmer summer and a colder winter than the northern.

If, however, it is hereafter shown that the mean temperature of the Arctic regions is much higher than that of the Antarctic, this will be amply accounted for by the influence of the warm currents of the Atlantic. Mr. Croll has shown what an enormous quantity of heat they carry northward; but there are no corresponding currents in the southern hemisphere. The currents that carry heat into the North Atlantic and the Arctic Ocean receive their direction, first from the coast of South America, which diverts the equatorial current to the north-west, and afterwards that of Europe, which diverts the Atlantic currents to the north-east*. Mr. Croll is probably right in supposing that the glaciation of the northern hemisphere would cause the north trade-wind to blow further south than at present, and that this would diminish the volume of the Gulf-stream, and so tend still further to lower the northern temperatures. But this cause would

* See 'Climate and Time,' map facing p. 212.

not act during the glaciation of the southern hemisphere, because, in consequence of the totally different disposition of the land, there are not in that hemisphere any great poleward currents.

My theory of the glacial climate, however, does not come into collision with Mr. Croll's on the subject of ocean currents, because the effect on climate of any change in the currents will be the same in kind, whether glaciation is caused by an aphelion winter or an aphelion summer. Such a change in the currents as Mr. Croll supposes cannot begin to act on climate until a change of climate has first begun to divert the currents. I think, however, that the cold of an aphelion summer at maximum eccentricity will amply account for the glacial climate by its direct effect, without any agency of ocean currents being needed.