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ON

GEOLOGICAL TIME,

AND THE

PROBABLE DATE OF THE GLACIAL AND THE UPPER MIOCENE PERIOD.

BY

JAMES CROLL,

OF THE GEOLOGICAL SURVEY OF SCOTLAND.

(Continued from vol. 35 p 382)

IT will not do, however, to measure marine denudation by the rate at which the sea is advancing on the land. There is no relation whatever between the rate at which the sea is *advancing* on the land and the rate at which the sea is *denuding* the land. For it is evident that as the subaërial agents bring the coast down to the sea-level, all that the sea has got to do is simply to advance, or at most to remove the loose materials which may lie in its path. The amount of denudation which has been effected by the sea during past geological ages, compared with what has been effected by subaërial agency, is evidently but trifling. Denudation is not the proper function of the sea. The great denuding agents are land-ice, frost, rain, running water, chemical agency, &c. The proper work which belongs to the sea is the transporting of the loose materials carried down by the rivers, and the spreading of these out so as to form the stratified beds of future ages.

We have thus seen that geology, alike with physics, is opposed to the idea of an unlimited age to our globe. And it is perfectly plain that if there be physical reasons, as there certainly are, for limiting the age of the earth to something less than 100 millions of years, geological phenomena, when properly interpreted, do not offer any opposition.

Perhaps one of the things which has tended to mislead on this point is a false analogy which is supposed to subsist between astronomy and geology, viz. that geology deals with unlimited *time*, as astronomy deals with unlimited *space*. A little consideration, however, will show that there is not much analogy between the two cases.

Astronomy deals with the countless worlds which lie spread out in the boundless infinity of space; but geology deals with but one world. No doubt both reason and analogy are favourable to the idea that the age of the material universe, like its magnitude, is immeasurable—although, however, we have no reason to conclude that it is eternal, any more than we have to conclude that it is infinite. But when we compare the age of the material universe with its magnitude, we must not take the age of one of its members (say, our globe) and compare it with the size of the universe. More than this, we must not take the age of all the presently existing systems of worlds and compare their age with the magnitude of the universe; but we must take the past history of the universe as it stretches back into the infinity of bygone *time*, and compare it with the presently existing universe as it stretches out on all sides into the infinity of *space*. For worlds precede worlds in time as worlds lie beyond worlds in space. Each world, each individual, each atom is evidently working out a final purpose, according to a plan prearranged and predetermined by the Divine Mind from all eternity. And each world, like each individual, when it serves the end for which it was called into existence, disappears to make room for others. This is the grand conception of the universe which naturally impresses itself on every thoughtful mind that has not got into confusion about those things called in science the Laws of Nature.

But the geologist does not pass back from world to world as they stand related to each other in the order of *succession in time*, as the astronomer passes from world to world as they stand related to each other in the order of *coexistence in space*. Besides, the researches of the geologist are not only confined to one world, but it is only a portion of the history of that one world that can come under his observation. The oldest of existing formations, so far as is yet known, the Laurentian Gneiss, are made up of the waste of previously existing rocks, and these, again, probably of the waste of rocks still prior. Regarding what succeeds these old Laurentians, geology tells us much; but regarding what preceded, we know nothing whatever. For anything that geology shows to the contrary, the time which may have elapsed from the solidifying of the earth's crust to the deposition of the Laurentians—an absolute blank—may have been as great as the time that has elapsed since then till the present day. Physical science limits the age of the globe to a period not exceeding something like 100 millions of years. Taking the age of the earth's crust at 100 millions of years, which probably is a high estimate, how long is it since the materials which now form these Laurentian rocks were laid down in the ancient sea-bottom in the form of sand and mud? This is a question which no one can answer; for we have no means of knowing how much of the 100 millions of years were exhausted before the Laurentian age. At all events, it must be very considerably less than 100 millions of years since the commencement of the Laurentian period.

Sir William Logan thinks that the time which separated the limestones containing the *Eozoon Canadense* from the Upper-Cambrian period may be as great as the time which elapsed between the Upper Cambrian and the nummulitic limestones of the Tertiary period. If this conjecture be anything like correct, then it is hardly possible that 50 millions of years can have elapsed since the Cambrian period. Assuming that the glacial epoch began about a quarter of a million years ago, and that the rate at which species change is uniform, we found that, adopting Sir Charles Lyell's mode of calculation, 60 millions of years have probably elapsed since the beginning of the Cambrian period. But I presume little or no weight can be placed on this mode of calculation; for it is based upon an assumption for which there is, I fear, very little warrant, viz. that the rate at which species change has been anything like uniform during geological ages. If any very great amount of time elapsed between the solidifying of the earth's crust and the Laurentian period, the probability is that the commencement of the Cambrian period does not date so far back as 60 millions of years.

Table I. shows the excentricity of the earth's orbit and longitude of the perihelion for 3 millions of years back, and 1 million of years to come, at periods fifty thousand years apart. From what we have already seen, it is very evident that 3 millions of years must stretch a considerable distance back into the geological history of our globe. And if geological climate depends upon, or is much affected by, the condition of the earth's orbit as regards excentricity, we have in this Table, combined with the other three, the means by which a rough idea of the character of the climate during at least a considerable portion of the Tertiary period may be arrived at.

Table I.

Number of years before A.D. 1800.	Excentricity of orbit.	Longitude of perihelion.	Number of years before and after A.D. 1800.	Excentricity of orbit.	Longitude of perihelion.
		° ′			° ′
−3,000,000	0·0365	39 30	−1,000,000	0·0151	248 22
−2,950,000	0·0170	210 39	− 950,000	0·0517	97 51
−2,900,000	0·0442	200 52	− 900,000	0·0102	135 2
−2,850,000	0·0416	0 18	− 850,000	0·0747	239 28
−2,800,000	0·0352	339 14	− 800,000	0·0132	343 49
−2,750,000	0·0326	161 22	− 750,000	0·0575	27 18
−2,700,000	0·0330	65 37	− 700,000	0·0220	208 13
−2,650,000	0·0053	318 40	− 650,000	0·0226	141 29
−2,600,000	0·0660	190 4	− 600,000	0·0417	32 34
−2,550,000	0·0167	298 34	− 550,000	0·0166	251 50
−2,500,000	0·0721	338 36	− 500,000	0·0388	193 56
−2,450,000	0·0252	109 33	− 450,000	0·0308	356 52
−2,400,000	0·0415	116 40	− 400,000	0·0170	290 7
−2,350,000	0·0281	308 23	− 350,000	0·0195	182 50
−2,300,000	0·0238	195 25	− 300,000	0·0424	23 29
−2,250,000	0·0328	141 18	− 250,000	0·0258	59 39
−2,200,000	0·0352	307 6	− 200,000	0·0569	168 18
−2,150,000	0·0183	307 5	− 150,000	0·0332	242 56
−2,100,000	0·0304	98 40	− 100,000	0·0473	316 18
−2,050,000	0·0170	334 46	− 50,000	0·0131	50 14
−2,000,000	0·0138	324 4	A.D. 1800. 0	0·0168	99 30
−1,950,000	0·0427	120 32	+ 50,000	0·0173	38 12
−1,900,000	0·0336	188 31	+ 100,000	0·0191	114 50
−1,850,000	0·0503	272 14	+ 150,000	0·0353	201 57
−1,800,000	0·0334	354 52	+ 200,000	0·0246	279 41
−1,750,000	0·0350	65 25	+ 250,000	0·0286	350 54
−1,700,000	0·0085	95 13	+ 300,000	0·0158	172 29
−1,650,000	0·0035	168 23	+ 350,000	0·0098	201 40
−1,600,000	0·0305	158 42	+ 400,000	0·0429	6 9
−1,550,000	0·0239	225 57	+ 450,000	0·0231	98 37
−1,500,000	0·0430	303 29	+ 500,000	0·0534	157 26
−1,450,000	0·0195	57 11	+ 550,000	0·0259	287 31
−1,400,000	0·0315	97 35	+ 600,000	0·0395	285 43
−1,350,000	0·0322	293 38	+ 650,000	0·0169	144 3
−1,300,000	0·0022	0 48	+ 700,000	0·0357	17 12
−1,250,000	0·0475	105 50	+ 750,000	0·0195	0 53
−1,200,000	0·0289	239 34	+ 800,000	0·0639	140 38
−1,150,000	0·0473	250 27	+ 850,000	0·0144	176 41
−1,100,000	0·0311	55 24	+ 900,000	0·0659	291 16
−1,000,000	0·0326	4 8	+ 950,000	0·0086	115 13
			+1,000,000	0·0528	57 31

On looking over Table I., it will be seen that there are three principal periods when the excentricity rose to a very high value, with a few subordinate maxima between. It will be perceived also that during each of those periods the excentricity does not remain at the same uniform value, but rises and falls, in one case twice, and in the other two cases three times. About 2,650,000 years back we have the excentricity almost at its inferior limit. It then begins to increase, and fifty thousand years afterwards, namely at 2,600,000 years ago, it reaches ·0660; fifty thousand years after this period it has diminished to ·0167, which is about its present value. It then begins to increase, and in another fifty thousand years, viz. at 2,500,000 years ago, it approaches to almost the superior limit, its value being then ·0721. It then begins to diminish, and at 2,450,000 years ago it has diminished to ·0252. These two maxima, separated by a minimum and extending over a period of 200,000 years, constitute the first great period of high excentricity. We then pass onwards for upwards of a million and a half years, and we come to the second great period. It consists of three maxima separated by two minima. The first maximum occurred at 950,000 years ago, the second or middle one at 850,000 years ago, and the third and last at 750,000 years ago—the whole extending over a period of nearly 300,000 years. Passing onwards for another million and half years, or to about 800,000 years in the future, we come to the third great period. It also consists of three maxima one hundred thousand years apart. These occur at the periods 800,000, 900,000, and 1,000,000 years to come, respectively, separated also by two minima. Those three great periods, two of them in the past and one of them in the future, included in the Table, are therefore separated from each other by an interval of upwards of 1,700,000 years.

In this Table there are three periods when the excentricity approaches to about its inferior limit, and the orbit becomes almost circular. The first is 2,650,000 years ago, when the excentricity was ·0053; the next is at 1,300,000 years ago, when it was only ·0022; and the next will occur in about 24,000 years hence, when its value will be ·0033. There is, therefore, an interval of 1,350,000 years between the minima in the one case, and an interval of 1,324,000 years in the other case.

The Table shows also four subordinate periods of high excentricity, of which the one that I have supposed corresponds to the glacial epoch is the chief. Three are in the past, and one in the future.

If the glacial epoch resulted from a high state of excentricity, there must have been at least five ice-periods, including the glacial epoch, during the past three millions of years—two as severe, and two much less severe than the glacial epoch.

It may be thought that so many as four or five ice-periods in the course of 3 millions of years past is inconsistent with the evidence of geology on that point. This, however, is at least very doubtful. It is quite possible that these three millions of years may embrace the greater part of the Tertiary period. Now we have evidence of at least three ice-periods since the beginning of the Tertiary period—one about the middle of the Eocene period, another during the Upper Miocene period, and the third and last the well-known glacial epoch*; and it is quite possible that the evidence of more may yet be found.

But before discussing the nature of the evidence which geology affords of the existence of former glacial periods, we shall turn our attention briefly to Tables II., III., and IV. These three Tables embrace the three periods of greatest excentricity during the past 3 millions of years. The excentricity, longitude of the perihelion, &c. are given at periods of ten thousand years apart.

There are still eminent astronomers and physicists who are of opinion that the climate of the globe never could have been seriously affected by changes in the excentricity of its orbit. This opinion results, no doubt, from viewing the question as a purely astronomical one. Viewed from an astronomical standpoint, as has been already remarked, there is actually nothing from which any one could reasonably conclude with certainty whether a change of excentricity would seriously affect climate or not. By means of astronomy we ascertain the extent of the excentricity at any given period, how much the winter may exceed the summer in length (or the reverse), how much the sun's heat is increased or decreased by a decrease or an increase of distance, and so forth; but we obtain no information whatever regarding how these will actually affect climate. This must be determined wholly from physical considerations, and it is an exceedingly complicated problem. An astronomer, unless he has given special attention to the physics of the question, is just as apt to come to a wrong conclusion as any one else. The question involves certain astronomical elements; but when these are determined, everything then connected with the matter is purely physical. Nearly all the astronomical elements of the question are comprehended in the accompanying Tables.

In Tables II., III. and IV., column I. represents the dates of the periods, column II. the excentricity, column III. the

* See Lyell's 'Principles,' vol. i. chap. x. (tenth edition).

longitude of the perihelion. In Table IV. the excentricity and the longitude of the perihelion of the six periods marked with an S are copied from a letter of Mr. Stone to Sir Charles Lyell, published in the Supplement of the Phil. Mag. for June 1865; the eight periods marked L are copied from M. Leverrier's Memoir in the *Connaissance des Temps* for 1843. For the correctness of everything else, both in this Table and in the other three, I alone am responsible.

Column IV. gives the number of degrees passed over by the perihelion during each 10,000 years. From this column it will be seen how irregular is the motion of the perihelion. At four different periods it had a retrograde motion for 20,000 years. Column V. shows the number of days by which the winter exceeds the summer when the winter occurs in aphelion. Column VI. shows the intensity of the sun's heat during midwinter, when the winter occurs in aphelion, the present midwinter intensity being taken at 1000. These six columns comprehend all the astronomical part of the Tables. Regarding the correctness of the principles upon which these columns are constructed, there is no diversity of opinion. But these columns afford no direct information as to the character of the climate, or how much the temperature is increased or diminished. To find this we pass on to columns VII., VIII. and IX., calculated on physical principles. Now, unless the physical principles upon which these three columns are calculated be wholly erroneous, undoubtedly change of excentricity must very seriously affect climate. Column VII. shows how many degrees Fahrenheit the temperature is lowered by a decrease in the intensity of the sun's heat corresponding to column VI. For example, 850,000 years ago, if the winters occurred then in aphelion, the direct heat of the sun during midwinter would be only $\frac{837}{1000}$ of what it is at present at the same season of the year. Column VII. shows that this decrease in the intensity of the sun's heat would lower the temperature 45°·3 F.

The principle upon which this result is arrived at is this:— The temperature of space, as determined by Sir John Herschel, is $-239°$ F. M. Pouillet, by a different method, arrived at almost the same result. Taking the midwinter temperature of Great Britain at 39°, consequently, $239°+39°=278°$ represent the number of degrees of rise due to the sun's heat at midwinter; in other words, it takes a quantity of sun-heat which we have represented by 1000 to maintain the temperature of the earth's surface at Great Britain 278° above the temperature of space. Were the sun extinguished, the temperature of our island would sink 278° below its present midwinter temperature, or to the temperature of space. But 850,000 years ago, if the

TABLE II.

I. Number of years before A.D. 1800.	II. Excentricity of orbit.	III. Longitude of perihelion.	IV. Number of degrees passed over by the perihelion. Motion retrograde at periods marked R.	Winter occurring in aphelion. V. Excess of winter over summer, in days.	VI. Midwinter intensity of the sun's heat. Present intensity = 1000.	VII. Number of degrees by which the midwinter temperature is lowered.	VIII. Midwinter temperature.	IX. Midwinter temperature, the Gulf-stream being diminished in proportion to the excentricity.
2,650,000	0·0053	318° 40′	95° 45′					
2,640,000	0·0173	54 25	39 12			F.	F.	F.
2,630,000	0·0331	93 37	33 35	15·4	906	26°·2	12°·8	6°·6
2,620,000	0·0479	127 12	31 24	22·2	884	33·3	5·7	− 3·3
2,610,000	0·0591	158 36	31 28	27·4	862	38·3	0·7	−10·5
2,600,000	0·0660	190 4	30 24	30·6	851	41·5	−2·5	−15·0
2,590,000	0·0666	220 28	29 28	30·9	850	41·8	−2·8	−15·4
2,580,000	0·0609	249 56	27 28	28·3	859	39·2	−0·2	−11·7
2,570,000	0·0492	277 24	27 38	22·9	878	33·9	5·1	− 4·2
2,560,000	0·0350	305 2	R 6 28	16·2	902	27·1	11·9	5·3
2,550,000	0·0167	298 34	R 44 36					
2,540,000	0·0192	253 58	5 21					
2,530,000	0·0369	259 19	23 48	17·1	899	28·0	11·0	4·0
2,520,000	0·0537	283 7	26 57	25·0	871	35·9	3·1	− 7·0
2,510,000	0·0660	310 4	28 32	30·6	851	41·5	−2·5	−15·0
2,500,000	0·0721	338 36	29 0	33·5	841	44·2	−5·2	−18·8
2,490,000	0·0722	7 36	28 10	33·6	841	44·3	−5·3	−19·0
2,480,000	0·0662	35 46	27 40	30·8	850	41·7	−2·7	−15·2
2,470,000	0·0553	63 26	25 47	25·7	868	36·6	2·4	− 8·1
2,460,000	0·0410	89 13	20 20	19·1	892	30·0	9·0	1·3
2,450,000	0·0252	109 33		11·7				

TABLE III.

1,000,000	0·0151	248 22	65 28					
990,000	0·0224	313 50	44 12					
980,000	0·0329	358 2	34 38	15·3	906	26·1	12·9	6·7
970,000	0·0441	32 40	34 9	20·5	887	31·5	7·5	−0·4
960,000	0·0491	66 49	31 2	22·8	878	33·8	5·2	−4·1
950,000	0·0517	97 51	29 51	24·0	874	35·0	4·0	−5·8
940,000	0·0495	127 42	28 29	23·0	878	34·0	5·0	−4·3
930,000	0·0423	156 11	25 29	19·7	890	30·6	8·4	0·4
920,000	0·0305	181 40	12 35	14·2	910	25·0	14·0	8·2
910,000	0·0156	194 15	R 59 13					
900,000	0·0102	135 2	R 8 1					
890,000	0·0285	127 1	25 32					
880,000	0·0456	152 33	27 50	21·2	884	32·2	6·8	− 2·0
870,000	0·0607	180 23	29 18	28·2	859	39·0	0·0	−11·5
860,000	0·0708	209 41	29 47	32·9	843	43·6	−4·6	−18·0
850,000	0·0747	239 28	29 46	34·7	837	45·3	−6·3	−20·3
840,000	0·0698	269 14	29 14	32·4	845	43 2	−4·2	−17·4
830,000	0·0623	298 28	27 36	29·0	857	40·0	−1·0	−12·8
820,000	0·0476	326 4	22 26	22·1	881	33·1	5·9	− 3·1
810,000	0·0296	348 30	R 4 41					
800,000	0·0132	343 49	R 50 30					
790,000	0·0171	293 19	10 18					
780,000	0·0325	303 37	25 1	15·2	907	26·0	13·0	6·7
770,000	0·0455	328 38	28 34	21·2	884	32·2	6·8	−2·0
760,000	0·0540	357 12	30 6	25·1	870	36·0	3·0	−7·2
750,000	0·0575	27 18	31 12	26·7	864	37·7	1·3	−9·5
740,000	0·0561	58 30	32 25	26·1	867	37·0	2·0	−8·6
730,000	0·0507	90 55	34 19	23·6	876	34·6	4·4	−5·2
720,000	0·0422	125 14	52 12	19·6	890	30·6	8·4	0·4
710,000	0·0307	177 26	30 47	14·3	910	25·0	14·0	8·2
700,000	0·0220	208 13						

Table IV.

I.	II.	III.	IV.	Winter occurring in aphelion.				
		Winter in Aphel.		V.	VI.	VII.	VIII.	IX.
Number of years before A.D. 1800.	Excentricity of orbit.	Longitude of perihelion.	Number of degrees passed over by the perihelion. Motion retrograde at periods marked R.	Excess of winter over summer, in days.	Midwinter intensity of the sun's heat. Present intensity =1000.	Number of degrees by which the midwinter temperature is lowered.	Midwinter temperature.	Midwinter temperature, the Gulf-stream being diminished in proportion to the excentricity.
250,000	0·0258	59° 39′	15° 19′			F.	F	F.
240,000	0·0374	74 58	27 51	17·4	898	28°·3	10°·7	3°·7
S 230,000	0·0477	102 49	21 44	22·2	885	33·2	5·8	−3·2
S 220,000	0·0497	124 33	20 22	23·2	877	34·1	4·9	−4·6
S 210,000	0·0575	144 55	23 23	26·7	864	37·7	1·3	−9·5
200,000	0·0569	168 18	21 46	26·5	865	37·4	1·6	−9·1
S 190,000	0·0532	190 4	19 18	24·7	871	35·7	3·3	−6·7
S 180,000	0·0476	209 22	18 45	22·1	881	33·1	5·9	−3·1
S 170,000	0·0437	228 7	8 31	20·3	887	31·3	7·7	−0·6
160,000	0·0364	236 38	6 18	16·9	900	27·8	11·2	4·3
150,000	0·0332	242 56	3 33	15·4	905	26·2	12·8	6·5
140,000	0·0346	246 29	13 5	16·1	903	26·9	12·1	5·6
130,000	0·0384	259 34	15 13	17·8	896	28·8	10·2	3·0
120,000	0·0431	274 47	19 1	20·1	888	31·0	8·0	−0·1
110,000	0·0460	293 48	22 30	21·4	883	32·4	6·6	−2·1
100,000	0·0473	316 18	23 44	22·0	881	33·0	6·0	−2·9
L 90,000	0·0452	340 2	24 11	21·0	885	32·0	7·0	−1·5
L 80,000	0·0398	4 13	23 9	18·5	894	29·4	9·6	2·1
L 70,000	0·0316	27 22	18 46	14·7	908	25·5	13·5	7·5
L 60,000	0·0218	46 8	4 6					
50,000	0·0131	50 14	R 21 38					
L 40,000	0·0109	28 36	R 22 46					
L 30,000	0·0151	5 50	38 10					
L 20,000	0·0188	44 0	34 28					
L 10,000	0·0187	78 28	21 2					
0	0·0168	99 30						

winters occurred in aphelion, the heat of the sun at midwinter would only equal 837 instead of 1000 as at present. Consequently, if it takes 1000 parts of heat to maintain the temperature 278° above the temperature of space, 837 parts of heat will only be able to maintain the temperature 232°·7 above the temperature of space; for 232°·7 is to 278 as 837 is to 1000. Therefore, if the temperature was then only 232°·7 above that of space, it would be 45°·3 below what it is at present.

This method of calculating how much the temperature is lowered by a given reduction of the sun's heat is that given by Sir John Herschel in his 'Outlines of Astronomy,' § 369 *a*. About three years ago, in an article in 'The Reader,' I endeavoured to show that this method is not rigidly correct. It results from the principles of the dynamical theory of heat, and is also supported by experiments made by Professor Draper, of New York, and others, that the rate at which a body radiates its heat off into space is not directly proportionate to its absolute temperature. The rate at which a body loses its heat as its temperature rises, increases more rapidly than the temperature. As a body rises in temperature, the rate at which it radiates off its heat increases; but the *rate* of this increase is not uniform, but increases with the temperature; consequently the temperature is not lowered in proportion to the decrease of the sun's heat. But this error is probably neutralized by one of an opposite nature, to which I shall now refer.

We know that absolute zero is at least 493° below the melting-point of ice; consequently, if the heat derived from the stars is able to maintain a temperature of −239° or 222° of absolute temperature, then nearly as much heat is derived from the stars as from the sun. But if so, why do the stars give so much heat and so very little light? If the radiation from the stars could maintain a thermometer 222° above absolute zero, then space must be far more transparent to heat-rays than to light-rays, or else the stars give out a great amount of heat but very little light, neither of which suppositions is probably true. The probability is, I venture to presume, that the temperature of space is not much above absolute zero. In this case, by adopting −239° as the temperature of space, we make the values given in column VII. too small. But as the two errors tend to neutralize each other, these values may in the meantime be accepted as not very far from the truth, or at least as near as can be arrived at in the present state of science on this point. But whether these values be too high or too low, one thing is certain, that a very slight increase or a very slight decrease in the quantity of heat received from the sun must affect temperature to a considerable extent. The direct heat of the moon, for example, cannot be detected by the finest instruments which we possess; yet from 238,000 observations made at Prague during 1840–66, it would seem that the temperature is sensibly affected by the mere change in the lunar perigee and inclination of the moon's orbit*.

Column VIII. gives the midwinter temperature. It is found by subtracting the numbers in column VII. from 39°, the midwinter temperature. Column IX. shows the midwinter temperature of the centre of Scotland, on the supposition that the Gulf-stream was diminished in volume in proportion to the excentricity. In former papers it was explained how a change of excentricity must affect ocean-currents†.

I have not given a Table showing the temperature of the summers at the corresponding periods. This could not well be done; for there is no relation at the periods in question between the intensity of the sun's heat and the temperature of the summers. One is apt to suppose, without due consideration, that the summers ought to be then as much warmer than they are at present, as the winters were then colder than now. Sir Charles Lyell, in his 'Principles,' has given a column of summer temperatures calculated upon this principle. Astronomically the principle is correct, but physically it is totally erroneous, and calculated to convey a wrong impression regarding the whole subject of geological climate. The summers at those periods, instead of being much warmer than they are at present, would in reality be far colder than they are now, notwithstanding the great increase in the intensity of the sun's heat resulting from the diminished distance of the sun. If a country is free from snow and ice, then no doubt the temperature will rise during summer as the intensity of the sun's heat increases; but when such a country is enveloped in perpetual snow and ice, the temperature of the summers will never rise much above the freezing-point, no matter what the intensity of the sun's heat may be. The physical reason of this was explained on a former occasion‡. In a country covered with ice, the direct heat of the sun is often very intense, in fact scorching. It will raise the temperature of the mercury in the thermometer exposed to the direct rays of the sun, but it fails to heat the air. Captain Scoresby, for example, when in lat. 80° 19′ N., found the side of his ship heated by the direct rays of the sun to about 100°,

* See Professor C. V. Zenger's paper "On the Periodic Change of Climate caused by the Moon," Phil. Mag. for June 1868.

† Phil. Mag. for August 1864 and February 1867.

‡ Phil. Mag. for February 1867.

while the air surrounding the ship was actually 18° below the freezing-point. On another occasion he found the pitch melting on the one side of the ship by the heat of the sun, while water was freezing on the other side from the intense coldness of the air.

The mean temperature of Van Rensselaer Harbour, in lat. 78° 37′ N., long. 70° 53′ W., was accurately determined from hourly observations made day and night over a period of two years by Dr. Kane. It was found to be as follows:—

Winter . .	−28°·59
Spring . . .	−10·59
Summer . .	+33·38
Autumn . .	− 4·03

But although the quantity of heat received from the sun at that latitude ought to have been greater during the summer than in England*, yet, nevertheless, the temperature is only 1°·38 above the freezing-point.

The temperature of Port Bowen, lat. 73° 14′ N., was found to be as follows:—

Winter . .	−25°·09
Spring . . .	− 5·77
Summer . .	+34·40
Autumn . .	+10·58

Here the summer is only 2°·4 above the freezing-point.

If we go to the Antartic regions, where the influence of ice is still more felt, we find the summers even still colder. Capt. Sir James Ross found, when between lat. 60° and 77° S., that the mean temperature never rose even to the freezing-point during the entire southern summer; and when near the ice-barrier on the 8th of February, 1841, a season of the year equivalent to August in England, he had the thermometer at 12° at noon, and so rapidly was the young ice forming around the ships that it was with difficulty that he escaped being frozen in for the winter. And on the February of the following year, when he again visited that place, he had the thermometer standing at 19° at noon, and the sea covered with an unbroken sheet of young ice as far as the eye could reach from the mast-head. This extraordinary low temperature at that season of the year was wholly owing to the presence of the ice. Had there been no ice on the Antarctic continent, Sir James would have had a summer

* See Mr. Meech's memoir "On the Intensity of the Sun's Heat and Light," Smithsonian Contributions, vol. ix.

hotter than that of England, instead of one actually below the freezing-point.

Now, during the glacial epoch, when Europe was almost covered with snow and ice, the summers could not possibly have been much warmer than they are at present in Arctic and Antarctic regions. In other words, during the glacial epoch the mean summer temperature would be very little above the freezing-point.

(To be continued)