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ON THE VARIATIONS OF THE CLIMATE OF THE GEOLOGICAL AND HISTORICAL PAST AND THEIR CAUSES.

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THIS paper is a revised and enlarged translation of a paper in Swedish, "Om klimatets ändringar i geologisk och historisk tid samt deras orsaker," published in *Ymer* (a journal edited by the Swedish Society for Anthropology and Geology), Stockholm, 1899, p. 353. It is an attempt to apply the results of physical, astronomical, and meteorological research in order to explain the secular changes of climate as recorded by geology and by history. I have in this paper endeavoured to avail myself of the works of eminent physicists, astronomers, and meteorologists, though I have not always accepted their results unaltered. For owing to the intricacy of the problems it may happen that a solution, mathematically and physically correct, does not correspond with the cosmical, geological, and meteorological facts it was intended to explain. Though not very familiar with geology, palæontology, or biology, I hope that, owing to the kind assistance of friends, I have been able to avoid misleading errors in that part of the matter. Several valuable treatises and other papers on geology have been consulted. I have sought throughout to do full justice to geological and biological evidence compared with that furnished by astronomy and physics.

For some leading ideas I am specially indebted to my good friends Prof. Svante Arrhenius and Dr. Gunnar Andersson.

On account of the simplicity and clearness of the metric system I have used it throughout, as well as centigrade degrees.

This paper is presented to the Royal Meteorological Society at its

Jubilee on April 3, 1900, as a humble expression of homage and gratitude by the author.

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1. *Introduction—On the general causes of changes of temperature.*

The phenomena of weather are of four principal classes, viz. those depending (1) on heat and light; (2) on water; (3) on air movement or wind; and (4) on electricity. Of these, the first is the most important, and is generally the cause of the others, light being only a development of heat. The heat economy of nature is thus the first chapter of every inquiry on climate, and temperature is the most important element of weather and climate. Temperature being also the element most easily examined and best known, I shall confine my inquiry to it. Thus the temperature of the atmosphere, of the ocean, and of the earth's surface determines, directly or indirectly, our climate. The temperature in its turn is determined by the insolation, *i.e.* the radiating energy (heat, light, etc.) of the sun, absorbed by the earth, and by the radiation from the earth into space, these two radiations being generally equal. But if the one varies without a proportional variation of the other, the temperature, and with it the climate, of the earth will undergo a general and radical variation, and *vice versâ*.

As will be shown further on, the solar constant, *i.e.* the heat radiation of the sun, has probably not undergone any serious changes during the time our earth has been an abode for life. But on the other hand, the transparency of the atmosphere for heat radiations of different kinds, and with it also the radiation from earth into space, have no doubt varied considerably, and thus produced the great climatic changes evidenced by geology.

Purely astronomical causes, such as the secular or long periodical changes of the eccentricity of the earth's orbit and of the obliquity of the ecliptic, are to be considered only in the second place.

Adhémar, Croll, Schmick, and others have tried to explain the Ice Age, though in a somewhat different way, by the difference in length of the summer and the winter halves of the year during the periods of great eccentricity of the earth's orbit, when the difference may amount to somewhat more than a month (35 to 36 days). But this explanation is untenable, for the simple reason that the total amount of heat which the short summer of the one hemisphere receives from the sun is equal to that which the long summer of the other hemisphere receives. Now, as the summer heat of our epoch, when this season has nearly its normal length, is more than sufficient to melt completely the winter snow in the regions of the earth which once were covered with ice, it certainly must be so even if the same quantity of heat be distributed over a somewhat shorter or somewhat longer space of time. And, in fact, the explanation of the Ice Age given by the above-named authors has not stood the test of scientific examination.[1] Yet it seems unquestionable that the long-period variations of the eccentricity of the earth's orbit, and those of the length of the four seasons following from them, will exert some influence on climate.[2] If, for instance, the summer be short and hot, and the winter long and cold, the climate will have quite a different character than if the summer be long and cool, and the winter short and mild. It will be a difference, as to temperature, essentially of the same kind as that between the climates of Siberia and of England, *i.e.* between the continental and the maritime climates. It is, however, doubtful if geologists have as yet discovered the traces of such periodical climatic changes as these, which, perhaps, are not very obvious.[3]

On the other hand, I shall prove further on that the long-period variations of the obliquity of the ecliptic have produced very marked periodic climatic changes in the north polar area, and south of it, at least as far as 55° N., and that these changes have left evident traces in the history of the earth, which already have been observed by geologists and botanists. It must be borne in mind that during the variations of the obliquity of the ecliptic the axis of the earth maintains its position in the earth itself invariable, the geographical position of any place on the earth's surface remaining undisturbed.

The case would be quite different if any considerable displacement of the axis of rotation relatively to the earth's figure had occurred. Then the climate of any place might be so radically altered that the pole, for instance, might change its climate with a place near the equator. Many geologists have supposed such changes as possible explanations of the great climatic variations of the geological past. But as the inquiries of modern geology unanimously indicate that all great climatic changes have occurred simultaneously on the whole earth, these changes cannot be explained by displacements of the poles, which would not alter the climate of the earth as a whole, but only transfer the climatic zones to other parts of the earth. Thus, even if such a displacement of the poles were mechanically possible, which is doubtful,

[1] J. Hann, *Handbuch der Klimatologie*, 2te Auflage, erster Band, Stuttgart, 1897, p. 370 and following. Also the present climatic state of the planet Mars seems to prove that a great eccentricity is unable to produce an Ice Age. For though the summer half-year of the southern hemisphere of Mars has a length of only 306 days, and that of the northern hemisphere one of 381 days, yet the white polar caps are melting away nearly completely every summer in both hemispheres. The planet passes its perihelion 36 days before the midsummer of its south pole, and the insolation in the perihelion bears to that in the aphelion a ratio of 1·45. Thus the contrast due to eccentricity is at present greater on Mars than it has ever been on the earth.

[2] J. Hann, *l.c.*

[3] According to the opinion of some geologists and botanists, especially of J. Croll and Axel Blytt, these climatic changes would also manifest themselves as changes in the rainfall, thus alternately producing dry and wet periods. As it seems to me at present impossible either to confirm or to disprove that opinion by means of physical or meteorological arguments, it may be left to future researches, and so much the more as the geological and botanical facts considered by Croll, Blytt, and their followers are still much in dispute.

we should nevertheless have no reason to enter on a discussion of that subject at present.

In the beginning, and about the middle, of this century it was a common opinion among geologists that the interior heat of the earth had materially contributed to the warm and uniform climate of the earliest geological periods. We shall see if there may possibly be any ground for this idea.

Once in primeval ages the earth must have been on the same stage of development as the planet Jupiter is at present. It was then surrounded by a very dense atmosphere, in which all water was suspended in form of vapour. The quantity of water being 244 times that of air,[1] the atmospheric pressure was then 245 times as great as at present, *i.e.* 245 atmospheres. Now, the critical temperature of water is 365° C., and the critical pressure 200 atmospheres. Accordingly, as long as the temperature of the earth's surface was above 365° C., the water immediately over it was maintained in the form of vapour, and the cooling was produced by convection by means of atmospheric currents and by thermal radiation at the upper limit of the atmosphere. Owing to the radiation, the upper strata of the vapour atmosphere were condensed to thick and perfectly opaque clouds,—as is now the case with the atmosphere of Jupiter,—and enormous showers were falling occasionally to the surface of the earth, producing spheroidal, or Leidenfrost, phenomena on a gigantic scale with violent explosions, and probably also volcanic eruptions, all which accelerated the cooling of the earth. This cooling was probably going on still faster as soon as the temperature of the surface had fallen below the critical temperature of water, for then the vapour would be condensed into a layer of water always increasing in thickness, and the atmosphere would become gradually translucid, so that heat would radiate directly from the surface of the water into space. As we know, vertical currents always arise in a mass of water heated at the bottom and cooled at the surface. These currents carry heat from below upwards, and thereby the whole ocean was rapidly cooled down to the temperature which it must finally assume as soon as equilibrium had been established between the heat received by the ocean from insolation and that lost by it by radiation into space. We find by calculation that it lasted only some hundred or at most one thousand years, till the ocean, after having taken the liquid state, was cooled down very nearly (within $\frac{1}{10}$° C.) to its final temperature.[2] Out of this time only a relatively little part was needed for

[1] According to Krümmel, the quantity of water amounts to 1285×10^6 km³. Thus, if it were uniformly spread over the whole surface of the globe, it would have a depth of 2520 metres, and the pressure of an atmosphere is exercised by a stratum of water $10\frac{1}{3}$ metres deep. The mean depth of the present oceans is taken as 3440 m.

[2] Let m denote the mass of the ocean, T_0 its absolute final temperature, S the number of calories which the ocean receives from the sun in one year = that which the ocean at the temperature T_0 radiates into space in one year, according to Stefan's law of radiation, *log* Briggs' logarithm, M its modulus, a the time in years, and T the absolute temperature of the ocean at the time a, further $a_{1,2}$ the number of years required for cooling from the absolute temperature T_1 to the absolute temperature T_2, we shall have

$$-m\,dT = S\left(\frac{T^4}{T_0^4} - 1\right)da$$

from which by integration

$$a_{1,2} = \frac{mT_0}{2S}\left\{\text{arc tan}\frac{T_2}{T_0} - \text{arc tan}\frac{T_1}{T_0} + \frac{1}{2M}\log\left(\frac{T_1 - T_0}{T_1 + T_0}\cdot\frac{T_2 + T_0}{T_2 - T_0}\right)\right\}$$

cooling from the critical temperature to 100° or 90° C., the temperatures at which life could begin to exist in the water.

But the cooled ocean in its turn cooled the bottom, and this by consequence contracted much more than the inner nucleus of the earth, so that frequent fissures, and with them volcanic eruptions, arose in the crust;[1] and a part of the water was pressed down into the fissures, giving rise to a great many hot springs at the bottom of the ocean. Owing to the feeble conductivity of the crust, this state might last very long, probably many millions of years, and during that time the lowest organic life might reach a relatively high development. During all that time volcanic forces were thus very active, and caused local heatings of the lowest layers of the water, which might have been very important to the life of some inferior organisms. But certainly the volcanic forces were much too feeble to cause any sensible heating of the whole ocean.

When these conditions had continued long enough, the bottom of the ocean and the earth strata under it to a considerable depth had been cooled down to temperatures which did not further vary sensibly with time. Thus a permanent state ensued, during which the heat brought to a stratum by conduction from beneath was exactly sufficient to supply the heat lost by conduction to the upper strata, and from the uppermost conducted to the ocean. By consequence, the volcanic forces entered on a time of repose, for the crust was no longer split by contraction relatively to the nucleus. But then gradually an opposite state arose in the crust. For the inner nucleus was always losing heat, and its temperature, in consequence, continually fell, though extremely slowly, whereas the crust maintained its temperature unaltered. Con-

Now, as shown further on (Chapter 3, p. 19), we may put, corresponding to the present conditions of the earth, $T_0 = 288°$ C., and $S = 720 \times 365{\cdot}24 \times 5{\cdot}1007 \times 10^{18}$ gram-calories, $5{\cdot}1007 \times 10^{18}$ being the area of the earth's surface in square centimetres. From hence, using Krümmel's value of m given above, we find $m/S = 0{\cdot}9590$. This means that it takes 0·9590 of a year to lower the temperature of the ocean, when it is 15° C., by one degree Centigrade. Then putting $T_0 = 273 + 15 = 288°$ C., $T_1 = 273 + 365 = 638°$ C., and $T_2 = 273 + 15{\cdot}1 = 288°{\cdot}1$ C., the above formula gives $a_{1,2} = 480$ years. And for the cooling from 90° to 50° C., for instance, we find $a_{1,2} = 40$ years. In the above calculation it was assumed that heat radiated directly from the ocean into space; but, as will be shown further on (Chapter 3, p. 14), the atmosphere absorbs a considerable part of the heat radiating from the ocean, and the phenomenon is going on just as if all heat radiated into space from an atmospheric layer of considerable height, and therefore at a much lower temperature than that of the ocean. In this case, if we assume corresponding values of T_0 and S, T_0 designating now the absolute temperature of that layer, it is easily seen (cf. the explanation given below, Chapter 3, pp. 19 and 20), that the above formula still remains true if we lower also T_1 and T_2 as much as we lower T_0. Thus lowering these three temperatures by 46° C., and taking for S half the above value, which corresponds approximately to the present state of the atmosphere, we find the time required for a cooling of the ocean from 365° to 15°·1 C. to be 790 years. It is probable that the absorbing power of the atmosphere was greater then than now, owing to the great quantity of water vapour in the atmosphere, and accordingly the time required for cooling the ocean, from the critical to the final temperature, may have been somewhat more than a thousand years. But we observe that the greatest part of that time was occupied in the cooling in the vicinity of the final temperature, as indicated by the formula, and, in consequence, that the ocean did not remain practically hot for more than some hundred years.

[1] As shown by Lord Kelvin (*Mathematical and Physical Papers*, vol. iii., London, 1890, p. 312 and following), the earth's nucleus is at least as rigid as steel or glass, in spite of its high temperature. This is explained by the enormously great pressure and high temperature by which the magma, though physically fluid or gaseous, obtains a viscosity or rigidity even greater than that of a solid at ordinary temperature. As soon as the pressure is suddenly diminished by the formation of a fissure, the magma becomes really fluid in the ordinary sense and is pressed up violently.

sequently the crust now expanded relatively to the nucleus, and by the action of gravity crumples were formed on it. In this way arose the first mountains and continents, which gradually lifted themselves above the level of the ocean. We will come back to this further on.

I shall now show that the conductivity of the crust is so insignificant that the heat brought by conduction from the inner hot nucleus to the ocean and atmosphere is entirely negligible compared with that supplied by insolation, and consequently cannot produce any sensible rise of temperature. The conductivity of primitive rock is at least thrice that of stratified rocks or deposits, such as sandstone, limestone, or marble; nevertheless it also is so insignificant that the primitive rock (granite) ought to be at a red-heat (1000° C. above the surface temperature) at a depth of 30 metres,[1] in order that the yearly quantity of heat furnished from the crust should amount to as much as the solar heat absorbed by the earth's surface and the lower atmospheric strata during the same interval. For a stratified rock the corresponding depth would be scarcely 10 metres. But it is very improbable that so great a rate of increase of the temperature with depth has ever occurred. And if so, it was certainly at the time when the temperature of the crust was higher than 365° C., and all the water was in form of vapour suspended in the atmosphere. For if the ocean had remained on so thin a crust, and that beneath it had been a glowing hot mass, the crust would have been incessantly torn in pieces by volcanic eruptions and explosions, until, by the cooling influence of the water, the temperature of the upper strata of the crust had immediately fallen so much as to make the rate of increase of the temperature with depth nearly as slow as in the present time. And even if this rate had once been much greater than now, which is improbable, the quantity of heat furnished from the interior of the earth would still have been nearly negligible compared with that of the sun. If, for instance, the temperature of primitive rock at a depth of 300 metres were 100° C. above that of the surface, the heat coming from the rock would be only $\frac{1}{100}$ of that from the sun.

Thus it results from the above that during the time organic life has existed on the earth the inner heat of the globe has not been able sensibly to raise either the mean temperature of the ocean or that of the air.[2] On the other hand, local heatings, as said above, in form of hot springs both on the sea bottom and the ground, may have played a considerable part for the organisms which thrive best at a high temperature. And as undoubtedly some centuries elapsed while the ocean was cooling down, we may assume that such organisms already then began to appear in it. If it be so, they will undoubtedly represent primeval life on the earth.[3]

[1] In this calculation I have used the coefficient of conductivity 0·582 gram-calories per minute, cm. and centigrade degree determined by Prof. Th. Homén in Finland; *Der tägliche Wärme-umsatz im Boden und die Wärmestrahlung zwischen Himmel und Erde*, p. 84. Leipsic, 1897.

[2] Lord Kelvin, by a somewhat different way of reasoning, has arrived at a similar result. W. Thomson, "On the Secular Cooling of the Earth," *Transact. of the Roy. Soc. of Edinburgh*, 1862; W. Thomson and P. G. Tait, *Treatise on Natural Philosophy*, vol. i. part ii., new edition, Cambridge, 1883, p. 448; W. Thomson, *Mathematical and Physical Papers*, vol. iii., London, 1890, p. 295.

[3] According to the Danish Prof. Eugen Warming (*Lehrbuch der ökologischen Pflan-*

Finally, I shall point out a thing which possibly may have played some part in vegetation during the older geological periods. No doubt Jupiter was then self-luminous, and its surface nearly as hot as that of the sun, and the heat and light radiated from this great planet to the earth, though, of course, much feebler than that from the sun, was perhaps not quite without influence.

2. *Geological chronology—The probable duration of life on the earth.*

Before beginning the study of the history of the climate on the earth, it will be desirable to fix a tolerably reliable chronology.

If here we ask the leading geologists, the answers run as follows. From the denudating force of rivers on stratified rocks Phillips has calculated that the age of these rocks is from 38 million to 96 million years.[1] Sir Archibald Geikie[2] makes the following calculation. The rate at which stratified deposits are formed varies from 1 foot in 730 years to 1 foot in 6800 years, and as the total thickness of all such strata, where fully developed, may be estimated to about 100,000 feet, we find the time elapsed during the formation of all such strata to lie between 73 million and 680 million years; and as new strata are also to a great extent built up from the detritus of older ones, these numbers are minimum values. By also taking this latter circumstance into account J. J. Sederholm[3] found the same interval to lie between 300 million and 1000 million years.

The following calculation of the age of the ocean was made by P. Mellard Reade, and communicated by T. C. Chamberlin.[4] The present quantity of common salt (sodium chloride) in the ocean is calculated to be 35,990 billion tons, and the yearly supply from the rivers 216 million tons. Supposing the yearly supply to have been formerly the

zengeographie, Berlin, 1896, pp. 157, 158), the *Schizophyceæ* (bluish-green algæ in a very primitive stage) thrive well in hot water of a temperature above 80° C. In North America, Yellowstone Park, these algæ are growing in water at from 30° to 85° C. "Do not these colonies of primitive algæ give us a representation of the oldest vegetation of the earth?" says Warming. The still more primitive sulphuric bacteria that are growing in knolls in hot springs in Japan thrive at temperatures between 51° and 70° C. (Manabu Miyoshi, *Studien über die Schwefelrasenbildung und die Schwefelbakterien der Thermen von Yumoto bei Nikko*, reprinted from the *Journal of the College of Science*, Imp. Univers., Tokyo, Japan, vol. x. part ii., 1897). Also a veritable green alga, a variety of *Conferva major*, and accordingly a much higher organism, is growing in water of 74° C. (Josephine E. Tilden, "Observations on some West American Thermal Algæ," in *The Botanical Gazette*, vol. xxv., January-June 1898, Chicago. As to the spores of bacteria, they can support, as known, still much higher temperatures; the spores of a bacterium growing in the earth at high temperatures are killed in saturated aqueous vapour at 100° C., but only after from five and a half to six hours. In superheated steam or hot air many spores endure still much higher temperatures, and are killed at 160° to 170° C., but only after an hour (Carl Günther, *Einführung in das Studium der Bakteriologie*, Leipzig, 1895). As to degrees of cold many seeds endure, without loss of germinating faculty, a temperature of −252° C., and probably, of course, also the absolute zero, −273° C. (W. T. Thiselton-Dyer and Dewar, *Proc. Roy. Soc.*, 1899, vol. lxv, p. 361). Prof. G. Lagerheim, at the University of Stockholm, who has kindly afforded me the above quotations, is, however, of the opinion that no spores or seeds will be able to endure these extremes of temperature during the thousands of years comprised in a geological period.

[1] Phillips, *Life on the Earth*, Rede Lecture, 1860, p. 119, cited by G. H. Darwin in *Nature*, vol. xxxiv. 1886, p. 420.

[2] Archibald Geikie, *Report of the British Association*, Edinburgh, 1892, Address, p. 19.

[3] J. J. Sederholm in the journal *Naturen*, May 15, 1894, Helsingfors, Finland (Swedish).

[4] *Journal of Geology*, vol. vii., Chicago, 1899, p. 572.

same as now, we find from this that it has taken 166 million years for the ocean to obtain its present quantity of sodium chloride. Now, on the one hand, we might possibly suppose that the yearly supply was greater in the oldest times than now; but, on the other hand, we know that enormous quantities of salt have crystallised out from the ocean and are forming thick layers of rock-salt. Thus the calculated time is rather too short than too long.

A. G. Nathorst[1] gives us a statement that enables us to make an approximate calculation of the time elapsed since the Silurian period. The contraction of the radius of the earth, owing to the secular cooling from that epoch to the present time, is estimated to at least 5000 metres. From this we first calculate the diminution of the mean temperature of the earth during that time to be at least 16° and at most 40° C.[2] Furthermore, we may calculate that, with the present conduction of heat, it will take at least 3 million, and perhaps as much as 11 million, years, before the mean temperature of the earth is lowered 1° C.[3] Hence it follows that from the Silurian period at least 48 million and perhaps as much as 440 million years have elapsed.

Another estimation of the contraction of the radius of the earth, due to Hein, would give values more than ten times as great as the above, for according to him this contraction, during the formation of the Alps, would be as much as 57 kilometres—a value which, however, is probably too high.[4]

Lord Kelvin[5] has calculated the secular cooling of the earth in another way and obtained smaller numbers—probably about 24 million years, according to the latest published estimate; whereas his first calculation gave more than 20 million and less than 400 million years, and probably about 100 million years. But the calculation of those results is based upon the following assumptions. Lord Kelvin starts from the hypothesis that the earth was once a glowing, melted mass, having the same temperature ($v_0 + V$) throughout, and being continuously cooled by

[1] A. G. Nathorst, *Jordens historia*, Stockholm, 1894, vol. i. p. 331 ("History of the Earth," Swedish, partly translated from M. Neumayr, *Erdgeschichte*, 1st edition).

[2] If we suppose the coefficient of linear expansion of the earth for one degree centigrade to lie between 0·00005 and 0·00002. The former value is probably, considering the high average temperature of the earth, nearer the truth.

[3] For the calculation we ought to know the specific heat on an average for the whole earth, as well as the thermal conductivity and the rate of increase of the temperature of the crust downwards (=the geothermal gradient) on an average for the whole surface crust. The specific heat of the upper crust is about a half per unit of volume; that of the deeper layers is probably greater. I have taken a half as a minimum value. From the laws of thermal conduction it follows that the geothermal gradient, when once a permanent state has commenced, will be approximately proportional to the reciprocal value of the coefficient of thermal conductivity, and therefore we ought to use corresponding values of these two constants by calculating the average conduction through the crust; but this meets with difficulties, as the geologists ordinarily determine only the former and the physicists only the latter. The mean thermal gradient is said to be 1° C. for 25 to 33 metres, and the coefficient of the thermal conductivity may be assumed to lie between 0·001 and 0·003 $\frac{\text{gram-calories}}{\text{cm. sec.}}$, and its probable value ought to be about 0·002, *i.e.* a little greater than that of marble.

[4] *Erdgeschichte*, von Prof. Dr. Melchior Neumayr, 2te Auflage, neubearbeitet von Prof. Dr. Viktor Uhlig, erster Band., *Allgemeine Geologie*, Leipsic and Vienna, 1895, p. 382.

[5] W. Thomson, *Transact. of the Roy. Soc. of Edinburgh*, 1862; *Mathematical and Physical Papers*, vol. iii. p. 295, London, 1890; W. Thomson and P. G. Tait, *Treatise on Natural Philosophy*, vol. i. pt. ii. new ed., Cambridge, 1883, p. 448; *Nature*, vol. li. 1894-1895, pp. 438-40.

thermal conduction from the interior outwards to the surface, where the temperature is supposed to have a lower constant value v_0. Thus the geothermal gradient is supposed to have been infinitely great at the earth's surface, but zero below the surface in the initial state. In order to maintain the surface temperature at the constant value v_0, he considers empty space as a body of physical matter having the same temperature $(v_0 - V)$ throughout, and the same conductivity as the earth. This latter assumption, of course, was introduced only in order to supply a law for the cooling of the earth's surface by radiation or convection of heat through the ocean and atmosphere. Further, the conductivity of the whole earth was assumed to be constant. Then applying the known theory of Fourier to this simple ideal case, he finds a formula[1] indicating that the geothermal gradient at the earth's surface will incessantly diminish, with increasing time, from its initial infinite value down to the present one. Then introducing in this formula a value of $v_0 + V$ equal to that of "melting rock," and taking for the present geothermal gradient in the surface $\frac{1}{51}°$ F. per foot, he obtained the above cited results.

Now for a moment accepting Lord Kelvin's final result, if we ask how long, after the initial state, the earth was fitted as an abode for life, we might perhaps assume that it was so, when the geothermal gradient of the surface had decreased to $\frac{1}{10}°$ per foot. Then we find from the formula that this decrease would take a time of only about one million years, and thus the earth would have been habitable during about 23 million years.

Every geologist and biologist will certainly think that both those periods are enormously underrated, and I shall now try to prove that they are so also on physical grounds. For this purpose we shall examine the above assumptions, from which Lord Kelvin starts.

Firstly, his law for the cooling of the earth's surface leads to a much too high rate of loss of heat, and in the initial state even to an infinite one. Lord Kelvin in his first cited paper meets this objection by the remark, that a large mass of melted rock, exposed freely to our air and sky, will, after it once becomes crusted over, present in a few

[1] The formula is—

$$\frac{dv}{dx} = \frac{V}{35 \cdot 4} \cdot \frac{1}{\sqrt{t}} e^{-\frac{x^2}{1600t}},$$

where $\frac{dv}{dx}$ designates the geothermal gradient in Fahrenheit degrees per foot, V half the difference of the two initial temperatures assumed on each side of the surface of the earth, x the depth below the surface in feet, and t the time in years. Thus at the beginning of the time $\frac{dv}{dx}$ is supposed to be infinite at the surface. If t be taken sufficiently great, the exponent may be neglected, and thus the exponential taken as equal to unity for small values of x, so that the use of the formula for the purpose in question is very simple. Now if the initial temperature of the earth, $v_0 + V$, be taken as equal to 7000° F., and v_0 be neglected as being nearly equal to zero, then if we put $\frac{dv}{dx} = \frac{1}{51}$, which is supposed to be the present value of the geothermal gradient in the surface (according to the observations), the formula gives $t = \left(\frac{7000 \times 51}{35 \cdot 4}\right)^2 =$ nearly 102 million years. In this way Lord Kelvin deduced the value of "about 100 million years." But afterwards taking for $v_0 + V$ only about 1200° C., and taking into account also the effect of pressure on the temperature of solidification, he obtained a value about four times less, which is his final result.

hours, or a few days, or at most in a few weeks, a surface so cool that it can be walked over with impunity. To this I remark that this was not so, until the earth's surface had already been cooled down so much, that the water had been condensed on it, and then the temperature of the crust was not higher than 365° C. or 689° F. Before that time the earth, as remarked above, was surrounded by a very dense and opaque atmosphere, just as Jupiter is now, and the loss of heat from the earth's surface was produced only by convection through the atmosphere and radiation at its upper limit, where the temperature was very low, and thus the loss of heat by radiation very little. Thus when the surface of the earth was cooling down from 7000° F., say, to 689° F., the loss of heat by convection and radiation was certainly incomparably much slower than according to Lord Kelvin's assumption, and thus also the time required for this cooling much longer than one million years.

We shall now consider the first of Lord Kelvin's assumptions, viz. that the earth in its initial state, or "*Consistentior Status*," had a uniform temperature throughout.

According to the nebular hypothesis, now generally accepted, the earth, as well as the other celestial bodies, was once a glowing gaseous mass. In that state of the earth its temperature certainly increased enormously from the surface to the centre. For heat was carried from the centre to the surface by convection, and as the pressure increased downwards, the matter, when sinking down, was heated by compression, and, when rising, was cooled by expansion. Also the surface, and the surface only, was cooled by radiation. In this way the gaseous globe incessantly lost heat, but, nevertheless, its inner temperature was continually rising, owing to the heat generated by contraction, just as, according to the theory of Helmholtz, the sun's heat is maintained in this manner.[1] When this process had been going on sufficiently long, the increasing temperature, pressure, and density of the nucleus produced so great a viscosity or rigidity in the gaseous mass, that the convectional currents were stopped, and then the surface layers relatively soon cooled down to a low temperature, so as to cover the nebula with a solid crust surrounded by a dense atmosphere. For the thermal conduction is much too slow to restore to the surface the heat lost by radiation. But just on account of the slowness of thermal conduction the inner nucleus maintained its enormously high temperature, or even grew hotter and hotter by self-compression, and, its temperature being much above the critical point, it remained in the gaseous state, *i.e.* conserved its perfect elasticity, though its viscosity or rigidity finally became equal to that of glass or steel. Such is, according to the modern view of physicists, the constitution of the earth's nucleus still to-day, and its present central temperature is estimated to about 100,000° C.[2] Only the crust, to a depth of perhaps 60 or 70 kilometres, can be in the solid state, but the underlying gas is, owing to the enormous pressure

[1] According to the calculations of J. H. Lane and Lord Kelvin, considered in a following chapter, the central temperature of a gaseous nebula is about $22\frac{1}{2}$ times higher than its average temperature, which is found to increase with time as the reciprocal of the radius of the nebula.

[2] See, for instance, S. Günther, *Handbuch der Geophysik*, Erster Band, p. 344 and following, Stuttgart, 1897.

and temperature, quite as rigid as a solid. Thus when the solidification of the crust took place, fragments of the shattered crust could not sink down in the inner nucleus, for this was already then about as rigid as glass or steel, and, moreover, much denser than the crust. In those points the views of Lord Kelvin were, in 1862, quite different, and he still seems to be of the opinion that the whole earth may be actually a kind of honey-combed solid and liquid mass of a nearly uniform temperature. But this view must now be considered as extremely improbable, since the numerous experiments of a great many physicists on the critical temperature and pressure, and especially the recent inquiries of Tammann on the constitution of matter at great pressures, have shown that neither the liquid nor the solid state can exist at very high pressures and temperatures.

Thus we must assume as the most probable case, that the inner nucleus of the earth in its "*Consistentior Status*" had a temperature of about 100,000° C. or 180,000° F. Now if this temperature be taken as the initial value of V in Lord Kelvin's formula instead of 7000° F. or 1200° C., and we by means of it calculate the time required for diminishing the geothermal gradient at the earth's surface from $\frac{1}{10}$° to $\frac{1}{51}$° per foot, then this time may be considered as an approximate value of the time during which the earth has been an abode fitted for life. Doing this we get as the age of life on the earth *many thousand million years.*[1] Such a value, which is deduced from Lord Kelvin's formula with the most probable value of the central temperature of the earth, will no doubt satisfy the requirements of geologists and biologists.

But if the geothermal gradient were really a measure of the earth's age, even such a gigantic number might be too small. For heat was generated, and is no doubt still generated, in the interior of the earth mechanically by its slow contraction, and this will probably suffice to maintain its inner temperature nearly constant during untold million years.[2] This circumstance alone would suffice to maintain the geothermal gradient at the surface constant during all the time this process is going on.

Also Lord Kelvin supposed the thermal conductivity of the earth to be constant. This assumption may be approximately true, if we assume, with him, the thermal state of the earth to be essentially variable, as presupposed in the formula. For then we must introduce in the formula the thermal conductivity measured in terms of the

[1] We find

$$t = \left(\frac{180,000}{35 \cdot 4}\right)^2 (51^2 - 10^2) = 64,700,000,000.$$

By this use of Lord Kelvin's formula we do not assume an initial uniform temperature through the whole earth, for we start from the initial state of a surface gradient of $\frac{1}{10}$° per foot, and then the formula indicates continual increase of temperature from zero at the surface to 180,000° F. at the centre; as it ought to be. As remarked by Lord Kelvin, his formula is deduced irrespectively of the earth's curvature, but at least during the first 1000 million years the variation of temperature does not become sensible at depths exceeding one-seventh of the earth's radius, and is therefore confined to so thin a crust that the influence of curvature may be neglected (*Math. and Phys. Papers, l.c.*, p. 302). And even during the first 10,000 million years the variation of temperature would be nearly insensible at depths exceeding one-third of the earth's radius.

[2] To a certain epoch the self-compression will even raise the temperature, then the temperature will remain very nearly constant during long ages, and finally very slowly decrease.

thermal capacity of unit of bulk.[1] But, as just shown, the thermal state of the inner nucleus of the earth is probably very nearly constant during untold million years, and the formula does not apply to such a permanent state, but only to a variable one. But for a permanent state we must calculate with the absolute conductivity, and this is at least thrice as great for primitive rock as for stratified deposits. Now nearly the whole surface of the earth is covered with thick layers of such deposits lying on primitive rock. But on account of the relatively great conductivity of the latter a great deal of heat is constantly carried to the inner surface of the stratified deposits, whereas their upper surface is constantly cooled by radiation and convection by air and water currents, so as to maintain its temperature very nearly equal to that of those currents. Hence it follows from the known laws of thermal conduction, that the stratified deposits will very soon after their formation be traversed by a regular flux of heat, forming a geothermal gradient proportional to the reciprocal value of the absolute conductivity of the stratified deposit, but independent of its age. Also it seems to me that this conclusion is verified by the observations, for the less the conductivity of a stratum is, the greater is generally the increase of heat in it with the depth, quite independently of its geological age.[2]

[1] Let κ be this conductivity, c the specific heat per unit of mass, δ the density, *i.e.* mass per unit of bulk, and k the absolute conductivity, *i.e.* the number of calories passing in unit of time through the unit of surface of a layer, the thickness of which is the unit of length, and the limiting surfaces of which are maintained at constant temperatures, differing by one degree, then

$$\kappa = \frac{k}{c\delta}.$$

[2] Thus in the Swedish iron mines the geothermal gradient is generally not more than $\frac{1}{50}$° C. per metre, or even less, in the artesian wells it is from $\frac{1}{38}$° to $\frac{1}{16}$°, and in coal mines even from $\frac{1}{14}$° to $\frac{1}{11}$° C. per metre. But as the geologists do not generally determine the conductivity of the strata, the geothermal gradient of which they measure, I cannot verify the above statement more in detail. I give here some values of absolute conductivity in the units of the Centimetre-Gramm-Second-System in order to prove the statement in a general way:—

Matter.	Absolute Conductivity.	Authority.
Pit-coal	0·000297	Neumann.
Slate	0·00081	Forbes.
Marble, white	0·00115	*Id.*
Marble, black	0·00177	*Id.*
Primitive rock	0·00970	Homén.

Lord Kelvin communicates in *Nature*, vol. li. p. 439, some values of thermal conductivity, due to R. Weber, and probably expressed in the above units. Also those values indicate the same fact, quartz having a much greater conductivity than the other minerals.

To those numbers it ought to be remarked that they, of course, apply only to ordinary temperatures. But in measuring the geothermal gradient in the earth's crust the observers did not in the greatest depths reached in mines and wells find temperatures exceeding 50° C. Thus the above numbers are applicable to the strata, where the geothermal gradients were observed. But if we calculate the geothermal gradient in the interior of the earth, where the temperature and pressure are very high, then we must confess that we know very little about the thermal conductivity of the matter there. It may be that the thermal conductivity of slate, sandstone, and granite is probably somewhat less at higher temperatures than at lower, as Lord Kelvin states (*l.c.* p. 439). But already in a depth of 60 or 70 kilometres (only about $\frac{1}{100}$ of the earth's radius) the temperature and pressure will be so high (temperature about 2000° C. and pressure about 10,000 atmospheres), that heat will be generated there or in a somewhat greater depth by the slow contraction of the crust. Thus the absolute conductivity in those depths is of little importance for the problem dealt with, though this conductivity probably still is greater than that of most stratified deposits at ordinary temperature.

According to Lord Kelvin there are some eruptive rocks of so recent origin that the permanent state has not yet set in, and thus their geothermal gradient is unusually great.

And in no case has the temperature of a stratified deposit decreased from its formation to the present time, for during its formation it had the same temperature as the water in which it was formed, and afterwards it was heated by thermal conduction from the ground, until the permanent state commenced.

I think the reasons adduced above will suffice to prove the probability of an already primeval, nearly permanent, state in the conduction of heat through the earth's crust. Hence it follows, that the geothermal gradient is not at all a measure of the earth's age, which for this quantity might be geologically nearly unlimited.

Thus I venture to say that the above method of calculation, used by myself, and founded upon the assumption of an already primeval permanent state in the geothermal gradient of the uppermost strata of the crust, is essentially correct, though the result obtained is, of course, uncertain, on account of the uncertainty of the physical constants employed.[1] There is, however, strong reason to believe that the limiting values of 48 million and 440 million years respectively, which I have found, are too small. For the heat generated by the earth's contraction enters into the calculation in the same manner as the specific heat of the earth, and thus increases the age calculated. If the heat of compression were, for instance, equal to the earth's own provision of thermometrical heat, the numbers found above ought to be doubled, and thus there would have elapsed between the Silurian and the present epoch at least 96 million and perhaps as much as 880 million years. The limiting numbers found by my calculation from the secular cooling of the earth are thus of the same order of magnitude as those obtained by geologists by means of quite different methods,[2] and thus we shall probably not err very much if we say that the age of life on the earth amounts to at least 100 million and perhaps to 1000 million years.[3]

In a popular lecture delivered by H. Helmholtz[4] at Königsberg in 1854 he calculated that since the beginning of the solar system the sun had generated by contraction, and lost by radiation, 28 million units of heat (centigrade) for each unit of its mass. Now, according to S. P. Langley, the sun's annual loss of heat by radiation amounts to somewhat more than two such units of heat per unit of mass, and thus the sun's provision of energy would only suffice for scarcely 14 million years, assuming the present rate of loss by radiation also for previous time, or, if the loss formerly were less than now, possibly some million years longer. But Helmholtz, in making this calculation, took into

But such exceptional cases are so rare that they are of no practical importance for the secular cooling of the earth. Sir W. Thomson, "On the use of Terrestrial Temperature for the Investigation of Absolute Dates in Geology," in *British Association Report*, 1855, part ii., reprinted in *Mathematical and Physical Papers*, vol. ii. p. 175, Cambridge, 1884.

[1] The greatest uncertainty is no doubt due to our ignorance of the real contraction of the earth's radius during geological time. But judging from the crumpling of the crust the value (5000 m.) given by Neumayr and Nathorst is no doubt too small, and thus the calculated time probably too short.

[2] The numbers found by Phillips, Archibald Geikie, Sederholm, and Mellard Reade are to be reckoned from the Precambrian or Cambrian time, and those found by myself from the Silurian; but this circumstance will be of no practical importance in dealing with such approximate methods of calculation.

[3] Archibald Geikie, *British Association Report*, Dover, 1899, Address to the Geological Section, p. 12.

[4] H. Helmholtz, *Ueber die Wechselwirkung der Naturkräfte, etc.*, Königsberg, 1854.

account only the work done by gravity in compressing the solar nebula, but not that done by the chemical and other molecular forces. Now, on the one side, these forces act only at very small distances, viz. between adjacent molecules and atoms; but, on the other hand, when they act at these microscopic distances they are enormously strong, a thousand, and perhaps even a million, times greater than gravity. Thus they must not be neglected, and though we do not know the intensity and radius of action of these forces so exactly that we are able to calculate the work done by them in the same way as that done by gravity, we may without hesitation estimate the work at least as ten times as much as that done by gravity, and accordingly replace the number of Helmholtz by at least 200 or 300 million units of heat (centigrade) per unit of mass of the sun.[1]

I have wished to show by the above that no valid reasons against the estimate of the age of life on the earth made by geologists and biologists can be taken from the laws and facts obtained from physical researches. It also seems to me that the geological and biological facts on which this estimate is founded are at least as reliable as the physical constants and assumptions on which a calculation of the secular cooling of the earth or the heat store of the sun are based. Still much more unreliable are the calculations of the earth's age founded on a hypothesis as to the mode of formation of the moon or the tidal friction exercised by it on the earth. For as long as Laplace's nebular hypothesis has not been verified by an exact mathematical analysis in all its consequences and details, we know nothing about the age of the moon as a satellite of our earth.

3. *The radiation of the sun nearly constant during geological ages.—The temperature at the earth's surface explained by the equilibrium between insolation and radiation from the earth into space.*

The nebular hypothesis for explaining the origin of the solar system, which was first set up by Emanuel Swedenborg in 1734, and then later developed by Immanuel Kant and in a more scientific form by Laplace, has gained a high degree of probability by the astronomical observations on nebulæ inaugurated by William Herschel, and so successfully carried on by means of the telescopic, photographic, and spectroscopic methods of modern astronomy. Nowadays we know that the immense universe is studded with innumerable nebulæ, which undoubtedly are the primitive stage of stars or solar systems. Some of them consist only of gaseous matter without definite outlines, others show already condensed portions, and a few are even well-defined stars surrounded by nebular matter. Most nebulæ exhibit a flattened spiral structure, thus indicating a rotatory motion. This hypothesis on solar evolution was completed in 1854 by Helmholtz,[2] who by his celebrated contraction

[1] The importance of the molecular forces for the store of energy of the sun has been particularly pointed out by Faye (*Comptes rendus, passim*). My friend Prof. Svante Arrhenius has made a calculation, not yet published, on this matter, and arrived at the result that the original store of potential energy in the sun owing to chemical forces was even much greater than according to the above estimate.

[2] H. Helmholtz, *l.c.*

theory showed that also the heat and light of the sun and the other stars may be explained as generated by the work done by the contraction. I have remarked above that the explanation of Helmholtz is incomplete, as he takes into account only the work done by gravity. But if this want be supplied by taking into account also the chemical, molecular, and other forces, if such exist, acting between the particles of matter, the theory given by Helmholtz will no doubt satisfactorily explain the provision of energy stored up in the sun, and will be found sufficient for the wants of geology.

The size of the sun is constantly decreasing, as, according to Helmholtz's theory, the sun is shrinking—so slowly that its apparent diameter will not diminish by $\frac{1}{16}$ second of arc in ten thousand years, if my estimate of its potential energy already given is correct. According to Helmholtz himself, the diminution would go on about ten times faster. As the angular momentum,[1] according to a known mechanical law, must remain constant during the contraction, we conclude that the sun has never reached as far as to the orbit of Mercury, the moment of rotation of which in its orbit around the sun is about 1900 times greater than that of a point of the sun's surface The radius of the sun can therefore never have been more than about 60 times greater than at present.

Now, if the temperature on the sun's surface had been constant during geological ages, it would have been at this early stage as high as it is at present, and hence the surface being then 3600 times greater than now, it would follow that the total amount of insolation must also have been then 3600 times greater than at present. But this is quite inadmissible. For life cannot have begun on the earth before the insolation had sunk to about the double of its present value (which with the present state of the atmosphere would produce a mean temperature on the earth's surface of nearly 70° C.), and the higher life can scarcely have begun before the insolation had sunk to about $1\frac{1}{2}$ of its present value (which with the present state would produce a mean temperature of nearly 46° C.).[2] Thus when it had been possible for life to begin on earth, the greatest part of the sun's heat store would already have been spent; and we find by calculation[3] that the age of life would be reduced to about 2,600,000 years, and that of higher life to about 1,800,000 years, if we assume Helmholtz's value of the heat store of the sun, or about ten times as much if we adopt my estimate. Also the whole age

[1] Let r be the distance of a particle from its centre of rotation and w its angular velocity, then the angular momentum, or moment of rotation, of the particle is wr^2. That $wr^2 =$ constant is the same mechanical law as the law of Kepler about the constancy of areas in a planetary orbit.

[2] The method of calculating these temperatures will be given further on.

[3] If t be the time in years and r the radius of the sun, then assuming that the work done by gravity be equal to the energy lost by radiation, we have

$$dt = c\frac{dr}{r^4},$$

c being a constant. Integrating and determining c by means of the condition, according to Helmholtz's and Langley's results, that the sun's radius is diminishing by $\frac{1}{1000}$ in 1200 years owing to the loss of heat by radiation, we find, if the present value of r be designated by r_0,

$$t = 4,000,000\left(1 - \frac{r_0^3}{r^3}\right).$$

of the solar system would be only 4,000,000 years according to Helmholtz's result, and 40,000,000 years according to my estimate. Thus the supposition of a constant temperature of the sun's surface during the geological ages would lead to so great a waste of the solar energy and thus to so short a time for the evolution of the solar system that it must be rejected merely for this reason.

Still more will this be the case with any hypothesis according to which the temperature of the sun's surface was in former times higher than now and decreasing up to the present time. Thus, for instance, the hypothesis of Eug. Dubois[1] is quite untenable. According to him,[2] the sun was, during the greatest part of geological ages, a white star, hotter than it is now, and then, during the Ice Age, it became suddenly a red star of lower temperature than the present one, and finally turned into its present condition of a yellow star of a middle temperature. Now, according to the estimate of J. Scheiner,[3] the surface temperature of a white star (I. spectral type) amounts up to about 15,000° C., that of a red one (III. spectral type) only to 3000° or 4000° C., that of a yellow one (II. spectral type) having an intermediate value. And according to my calculation, adopting Langley's value of the solar constant and Stefan's law of radiation, the actual temperature of the sun's surface is 6600° C. absolute. Thus the surface temperature of a white, a yellow, and a red star will be approximately as $2 : 1 : \frac{1}{2}$, and hence, according to Stefan's law of radiation, the radiating power per unit of surface as $2^4 : 1 : (\frac{1}{2})^4$, *i.e.* as $16 : 1 : \frac{1}{16}$. But if the radiating power of the sun were 16 times as great as its present value, the mean temperature on the earth would be as high as about 576° absolute, or 303° C.; and if it were only $\frac{1}{16}$ of the present value, this temperature would be as low as about 144° absolute, or − 129° C. Thus in neither case could life exist on the earth.

Thus there can be no doubt that the temperature of the sun's surface increases with time as the sun contracts, and thereby the area of its radiating surface decreases. And in fact the physical inquiry into the problem has also led to this same conclusion.

Such inquiries have been made by J. H. Lane,[4] A. Ritter,[5] and Lord Kelvin,[6] and I have tried to work out these inquiries further and draw some consequences therefrom.[7]

The three physicists above-named start from the following assumptions. A nebula or a sun is a mass of glowing gas which, according to the theory of Helmholtz, is heated by the work done by gravity in contracting it, and loses heat by radiation from its surface. The heat generated in the interior is carried to the surface by convectional currents, of which the temperature is calculated according to the mechanical theory of heat as a function of the pressure or the density of the gas, assuming for the relation between temperature, pressure,

[1] Eug. Dubois, *The Climates of the Geological Past*, etc., London, 1895.
[2] *l.c.* p. 99.
[3] J. Scheiner, *Sitz. ber. d. Berlin. Akad.* 1894, Nr. 12, 257.
[4] J. H. Lane, *Amer. Journ. of Science and Arts*, 2 Ser., 50, 1870, p. 57.
[5] A. Ritter, *Wied. Ann.* 5-20, 1878-82 (several papers).
[6] W. Thomson, *Proc. of the Roy. Soc. of Edinburgh*, vol. xiv., 1886-87, pp. 111, 118.
[7] Nils Ekholm, "Ueber den Energie-Vorrath, die Temperatur und Strahlung der Weltkörper," in *Bihang till K. Sv. Vet.-Ak. Handl.* Bd. 26, Afd. I., No. 1, Stockholm, 1900.

and density (or volume) the laws of Mariotte and Gay-Lussac. This gives the result that the absolute temperature of the sun, when contracting, will increase with time as the reciprocal of its radius; and as, according to Stefan's law, the radiation per unit of surface varies as the fourth power of the absolute temperature, it follows that the total amount of insolation will increase with time, as the sun contracts, as the square of the reciprocal of its radius. This, of course, would be so speedy an increase of the insolation, and thus presuppose so feeble an insolation in ancient times, that it is inadmissible on geological grounds. But it is also inadmissible on physical grounds. For we know from physical experiments that Boyle's law is not valid at pressures of more than one or two hundred atmospheres, whereas the pressure in the interior of the sun amounts to thousands of million atmospheres.[1] Thus we conclude that the above result will be true only as long as the gaseous nebula is very thin and has an enormously great volume. As to the sun, the result has never been exactly true; for, as stated above, the sun cannot possibly have had a radius more than sixty times greater than the present. But we may assume that the result was approximately true during the first stage of the sun's evolution, and thus that the insolation was then rapidly increasing. But after a relatively short time the increase must stop and the insolation become approximately constant. For though we cannot at present solve the proposed problem rigorously by introducing the true and general equation of the gaseous state of matter instead of the equation of Boyle-Charles, we can find from approximations that the increase of the sun's temperature must go on much slower than it would do according to the above simple solution. Moreover, the convection of heat from the inner parts to the surface will be gradually retarded as the sun grows hotter and denser. For the inner friction of a gas increases rapidly with temperature, and the astronomers best acquainted with solar physics are of the opinion that the gaseous matter of the sun within the photosphere is at present at least as viscous as honey or tar. Thus the surface temperature, and accordingly the radiation from the surface, will increase much less rapidly than the inner or mean temperature of the sun. Considering all this, it will seem probable that the total amount of insolation increased during the first stage of the sun's evolution, but that this increase gradually became slower and that the insolation has been nearly constant during all the time life has existed on the earth. We may assume that the insolation has varied from the Archæan to the present time perhaps as much as from the half of its present value up to this. But there is no reason to assume long periodical variations of greater amount. And certainly the great climatic changes revealed by geological inquiries cannot be attributed to any such variations of insolation.

But, as already remarked in Chapter 1, the temperature of the earth's surface is a function not only of the insolation, *i.e.* supply of heat, but also of the radiation from earth into space, *i.e.* loss of heat, and the latter will vary considerably if the transparency of the atmo-

[1] The absurd consequences following from the Lane-Kelvin theory, if applied without limitation to the state of the sun, have been clearly formulated by T. C. Chamberlin, *Science*, N.S., vol. ix. pp. 889-901, 1899; and vol. x. pp. 11-18, 1899.

sphere for heat radiations of different kinds varies. Practically a variation of the transparency of the atmosphere will have nearly the same effect as a variation of the solar constant, and according to this we can find a very simple method of approximately calculating the mean temperature of the earth's surface under different conditions. This will now be shown.

We know that the sun is practically the only source of warmth to provide the atmosphere, the ocean, and the earth's surface with their store of heat. Compared with it both the inner heat of the earth and the radiating heat of the stars are quite insignificant. From the observations on nocturnal radiation made by Liais, Langley[1] has calculated that the temperature of empty space is − 268° C., or 5° C. absolute. According to S. Newcomb, the light of the sun is 31 million times stronger than that emitted from all stars, and hence, assuming that the radiant heat is proportional to the radiant light, I find, by means of Stefan's law of radiation, that the mean temperature of space, owing to the radiation of stars, is about 4° C. absolute, a value which nearly agrees with Langley's result. Thus the heat radiation of space is so insignificant that it may be neglected without sensible error.

Knowing the temperature of space, we may now calculate the earth's loss of heat by radiation into space. Let U be the radiation from a warmer to a colder body during 24 hours in gram-calories per square centimetre, then, according to Stefan,

$$U = 0{\cdot}0000001045(T^4 - t^4),$$

T designating the absolute centigrade temperature of the warmer and t that of the colder body, when both bodies are perfectly black.[2]

Tabulating this formula, putting for t the value 5° or 4° C. absolute (which may be neglected), we find :—

TABLE I.—Loss of Heat by Radiation into Space from a perfectly Black Body of the Temperature t° Centigrade. In Gram-Calories per Square Centimetre during 24 Hours.

t	Loss of Heat.	t	Loss of Heat.	t	Loss of Heat.
100°	2023	20°	770	− 60°	215
90	1816	10	670	− 70	178
80	1624	0	581	− 80	145
70	1447	− 10	500	− 90	117
60	1285	− 20	428	− 100	94
50	1138	− 30	365	− 110	74
40	1003	− 40	308	− 120	57
30	881	− 50	259	− 130	44

For the low temperatures above tabulated we may assume, without sensible error, that clouds, atmosphere, ground, water, ice and snow,

[1] S. P. Langley, "The Temperature of the Moon," *Mem. of the Nat. Academy*, vol. iv., 9th mem., 1890, p. 206 and following.

[2] A newer determination of the constant of Stefan's formula, due to Kurlbaum, gives the value 0·0000001106. The difference is of no or little importance. I have used the above value.

etc., radiate as much heat as black bodies, and thus that this table is to be applied, without correction, to the radiation of the earth.

Now, as the mean temperature of the earth's surface remains very nearly constant during hundreds of years, the loss due to radiation must be equal to the gain of heat due to insolation. But this gain cannot be directly determined by experience; for though we know approximately the total amount of insolation falling on the earth's surface by the experiments of Langley and others, we do not know how much of it is absorbed. In fact, a considerable part of the solar rays is reflected back into space without being absorbed. The clouds, atmosphere, ground, water, and ice, though very nearly black for the radiation from the earth, are not so for the solar rays; or, in other words, the earth has a great albedo, the value of which is very imperfectly known, for the solar radiation.

According to Langley, the solar constant amounts to 3 gram-calories per square centimetre during a minute, which corresponds to an average for the whole earth of 1080 gram-calories per square centimetre during 24 hours. If all this heat were absorbed, the loss of heat, according to Table I., would also be 1080 calories; and we find by interpolation in the Table that the mean temperature of the earth's surface would be 46° C. Now the actual mean temperature of the earth's surface, derived from meteorological observations, is 15°·1 C., which, according to the table, corresponds to a daily mean quantity of heat absorbed equal to 720 calories, or only two-thirds of what it would be according to Langley's value of the solar constant.

The temperatures given above (pp. 15 and 16) for different values of insolation have been calculated by means of Table I. or by Stefan's formula in the manner here explained.

All the above calculations have been made as if the earth's surface were the only matter absorbing, emitting, and reflecting heat. This, of course, is only a first approximation, for the atmosphere plays a great and very complicated part in the phenomenon. An elaborate inquiry on this complicated phenomenon has been made by Svante Arrhenius.[1]

The result of that inquiry may be summed up as follows. The atmosphere plays a very important part of a double character as to the temperature at the earth's surface, of which the one was first pointed out by Fourier, the other by Tyndall. Firstly, the atmosphere may act like the glass of a green-house, letting through the light rays of the sun relatively easily, and absorbing a great part of the dark rays emitted from the ground, and it thereby may raise the mean temperature of the earth's surface. Secondly, the atmosphere acts as a heat store placed between the relatively warm ground and the cold space, and thereby lessens in a high degree the annual, diurnal, and local variations of the temperature.

There are two qualities of the atmosphere that produce these effects.

[1] Svante Arrhenius, "Ueber den Einfluss des atmosphärischen Kohlensuäregehalts auf die Temperatur der Erdoberfläche," in *Bih. till K. Iv. Vet.-Akad. Handl.* Bd. 22, Afd. I., No. 1, Stockholm, 1896; "On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground," in *Phil. Mag.* for April 1896, p. 237; "Naturens värmehushållning" (Heat Economy of Nature), in *Nordisk Tidskrift*, Stockholm, 1896, p. 121; "Les oscillations séculaire de la température à la surface terrestre," Extrait de la *Revue générale des Sciences* du 15 Mai 1899, Paris, 1899.

The one is that the temperature of the atmosphere generally decreases with the height above the ground or the sea-level, owing partly to the dynamical heating of descending air currents and the dynamical cooling of ascending ones, as is explained in the mechanical theory of heat. The other is that the atmosphere, absorbing but little of the insolation and the most of the radiation from the ground, receives a considerable part of its heat store from the ground by means of radiation, contact, convection, and conduction, whereas the earth's surface is heated principally by direct radiation from the sun through the transparent air.

It follows from this that the radiation from the earth into space does not go on directly from the ground, but on the average from a layer of the atmosphere having a considerable height above sea-level. The height of that layer depends on the thermal quality of the atmosphere, and will vary with that quality. The greater is the absorbing power of the air for heat rays emitted from the ground, the higher will that layer be. But the higher the layer, the lower is its temperature relatively to that of the ground; and as the radiation from the layer into space is the less the lower its temperature is, it follows that the ground will be hotter the higher the radiating layer is.

Now if we are able to calculate or estimate how much the mean temperature of that layer is lower than the mean temperature of the ground, we may apply Table I. for calculating the mean temperature of the ground, as soon as we know by direct measurements the quantity of solar heat absorbed by the ground. Owing to the clouds and dust floating in the atmosphere, this heat is probably only about a third of that derived by using Langley's solar constant; and is thus about 360 calories per square centimetre during twenty-four hours. This gives, by means of Table I., a temperature of $-31°$ C. to the radiating layer. But, according to Arrhenius's estimate, this is at a height of about 7600 metres;[1] and assuming a decrease of the temperature with the height of 0°·6 C. per 100 metres, we find its temperature to be 46° C. lower than that of the ground, and thus the mean temperature of the ground equal to 15° C., as it is according to the observations. This example, of which the numbers given do not pretend to be exactly true, shows the method of calculation. We see from it that both the absorbing power of the atmosphere for the heat radiation of the ground, and the quantity of clouds and dust in the atmosphere play an important part as regards the temperature of the ground. By the former the temperature is raised, by the latter it is lowered. We shall now enter more fully on the consequences of this important question.

4. *Variations in the quantity of carbonic acid of the atmosphere, the principal cause of the great climatic variations during geological ages.*

Among all the numerous hypotheses[2] imagined in order to explain the great climatic changes of the geological ages, that worked out by

[1] For the carbonic acid alone at 15,000 metres, and for the water vapour alone at 233 metres on an average.

[2] An elaborate study of the historical part of this question has been made by Luigi de Marchi, "Le cause dell' era glaciale," premiato dal R. Istituto Lombardo, Pavia, 1895.

S. Arrhenius[1] on the ground gradually laid by Fourier, Pouillet, Tyndall, Langley, Knut Ångstrom, Paschen, and others is the only one which has stood the test of a scientific examination. It is founded on the fact that carbonic acid, though as transparent as pure air to the solar rays, is partly opaque to the heat radiating from the ground and the lower and warmer strata of the atmosphere. Owing to this the carbonic acid in the atmosphere acts as the glass of a green house, letting through the solar rays, but partly retaining the dark rays emitted from the ground. Thus, if the quantity of carbonic acid in the atmosphere increases, the temperature of the ground and the lower atmospheric strata will be raised, till the increase of radiation into space caused by the increase of temperature has restored the equilibrium between gain and loss of heat. But to this is added a circumstance which considerably adds to the influence of the carbonic acid. Aqueous vapour possesses the same remarkable property as carbonic acid, and is nearly transparent to solar heat, and nearly opaque to terrestrial heat. Aqueous vapour alone is, however, unable to produce any radical change of climate. For the quantity of aqueous vapour in the atmosphere is itself depending upon the temperature of the air; if this be lowered by some cause, for instance by radiation, the aqueous vapour is partly condensed and separated from the atmosphere, whereby its protecting influence is diminished, and then the increased radiation causes a new condensation of vapour, and so on. It is, therefore, only in regions and seasons already favoured by nature with a warm and damp climate that aqueous vapour alone is able to play the part of green-house glass; whereas in cold and dry regions, where the protection is most needed, aqueous vapour fails.

The case will be quite different when the carbonic acid comes into play. This gas is not condensed at any temperature occurring in the lower strata of the air. Its protecting power is thus equally active in all climates. If now the quantity of carbonic acid increases, the temperature, as already stated, will rise. But thereby also evaporation, and, of course, the quantity of aqueous vapour in the air, will be increased, by which the radiation from earth into space will be still diminished. Accordingly, the temperature will be further raised, and thus also evaporation and aqueous vapour in the atmosphere increase, and this will continue till the increase of radiation into space puts an end to the rise of temperature. In this manner the protecting influence of carbonic acid is considerably augmented by the co-operation of aqueous vapour. The chief results of Arrhenius's calculation are contained in Table II. This table was calculated chiefly by means of Langley's measurements of the heat radiation of the moon. A new determination of the absorbing power of carbonic acid at low temperatures just made by Arrhenius and not yet completely calculated, seems to lead to results not differing materially from those of Table II.

If the quantity of carbonic acid varies by a geometrical series, the temperature will vary approximately by an arithmetical one.

Now if we remember how insignificant is the present quantity of carbonic acid in the atmosphere we shall be surprised at the great effects produced by halving or doubling it. In the former case we should have

[1] Svante Arrhenius, *l.c.*

a lowering of the temperature by 5° to 6° C., which is more than is needed in order to change the climate of the earth to that which prevailed during the Great Ice Age. The snow-line is then estimated to have been about 1000 metres lower than now, and this corresponds to a lowering of the temperature equal to 4° or 5° C.

TABLE II.—VARIATION OF THE MEAN YEARLY TEMPERATURE OWING TO A GIVEN VARIATION OF THE QUANTITY OF CARBONIC ACID IN THE ATMOSPHERE.

The present quantity of carbonic acid = 1; + signifies rise, – fall of the temperature. Centigrade degrees.

Latitude.	Quantity of Carbonic Acid.				
	⅔	1½	2	2½	3
65° N.	–3·1°	+3·5°	+6·1°	+8·0°	+9·3°
55	–3·2	+3·6	+6·0	+7·9	+9·3
45	–3·3	+3·7	+5·9	+7·7	+9·2
35	–3·3	+3·5	+5·7	+7·4	+8·8
25	–3·2	+3·5	+5·3	+6·9	+8·1
15	–3·1	+3·3	+5·0	+6·5	+7·5
5	–3·0	+3·2	+4·9	+6·4	+7·3
5° S.	–3·0	+3·2	+5·0	+6·5	+7·4
15	–3·1	+3·2	+5·1	+6·7	+7·6
25	–3·2	+3·3	+5·4	+6·9	+8·2
35	–3·3	+3·5	+5·6	+7·3	+8·8
45	–3·4	+3·7	+6·0	+7·9	+9·3

On the other hand, a tripling of the quantity of carbonic acid would raise the temperature by from 7° to 9° C., which would suffice to give to South Sweden (55° N.) the climate of North Italy, and to Italy that of the Torrid Zone. The Polar Regions would thereby obtain a temperate climate.

There are several reasons, however, to believe that the influence of the quantity of carbonic acid of the atmosphere on the mean temperature of the ground may be in certain instances still greater than according to the Table just given, as Arrhenius himself remarks, at the end of his first-mentioned paper. The latest measurements of the decrease of the temperature with the height, made in France and Germany, have shown that this decrease is probably much greater in the middle latitudes of Europe than Glaisher's observations indicate. Hence it follows, according to the deduction on page 20, that also the warming influence of the carbonic acid must be greater than according to Table II., which was calculated by means of Glaisher's values. This conclusion, of course, holds good only for those parts of the earth and for those seasons in which the decrease of temperature with the height is as great as the above-named French and German observations indicate. I shall now consider this point more in detail.

Our knowledge of the variation of the temperature of the atmosphere with the height above sea-level is very imperfect indeed. Especially we know very little about that variation in the Arctic Regions and at the great centres of cold in the northern continents during winter. There the mean temperature of the lowest layers of the air generally sinks below –40° C. and a temperature of –50° or –60° C. seems not to be rare. A minimum of −50° C. has been observed in the centre of cold in North Scandinavia.[1] Nansen observed a minimum of −52°·6 C. during the voyage with the *Fram*, and at Werchojansk in Siberia the absolute minimum hitherto observed is −69°·8 C. There are, however, strong reasons to believe that the temperature of the air in the layers above these centres of cold is higher than in those nearer to the earth's surface. Thus, for instance, the Swedish geologists, especially Axel Hamberg, have placed minimum thermometers on mountain tops in Lapland (North Sweden). Hamberg[2] found in 2100 metres above sea-level an absolute minimum of not more than −27°·8 C., and a comparison with the minima at adjacent low stations (200 to 300 metres above sea-level) gave the result that the minimum at the top was about 10° C. higher than it was at the low stations. The meteorological observations arranged by J. Hann and others in the Alps have given a similar result. Also a consideration of the general state of the weather during the periods of such extreme cold leads to the conclusion that in those regions the temperature at a higher level is higher than near the ground. For when the weather is anticyclonic the air is slowly sinking down over those regions, and thereby dynamically heated. But near the ground the air cooled by radiation is nearly stagnant and in very stable equilibrium, so that the warmer air in the higher levels is probably flowing over it outwards from the centre of the anticyclone without reaching the ground. Thus over those cooled regions there is, probably to a considerable height, an increase of temperature with the height, and this is called temperature inversion.

As now in those centres of cold the warming influence of the insolation is very feeble or zero (as such weather occurs in the winter in high latitudes), and as the air circulation is such as to prevent all heating by means of air currents coming from warmer regions, the only source of heat is the feeble radiation from the upper dynamically heated air. Simultaneously the radiation from earth into space is relatively unimpeded, the sky over an anticyclone being relatively clear. Thus the severe cold is explained, and it will be obvious that the protecting influence of the carbonic acid is very much enfeebled by those circumstances, so much the more so as the quantity of water vapour is insignificant, partly owing to the low temperature, partly on account of the downward movement of the upper air. Also the snow covering of the ground is very favourable for the development and permanence of such a state of weather, for the snow radiates heat as a black body, and being a very bad conductor of heat, completely hinders the supply of heat from the ground; also the evaporation from the cooled snow surface is nearly insensible, and often the snow, instead of evaporating, condenses the aqueous vapour in the air on its surface.

By comparing this state of weather with the general state according to the description given above (p. 20), we see that it is, up to a considerable height above sea-level, the complete inversion of the general

[1] About 69° N. and 25° E. from Greenwich. As to the state of temperature of the Scandinavian Peninsula, I refer to my paper on this matter in *Ymer*, 1899, p. 221 and following, with 6 charts.

[2] Axel Hamberg, *Ymer*, journal edited by the Swedish Society for Anthropology and Geography, Stockholm, 1899, p. 463 (Swedish).

state, the temperature increasing upwards from the ground instead of decreasing. How great this height is we do not yet know, but evidently it is more than 2000 metres in Lapland, and perhaps the radiating layer, the mean height of which in this case is about 15,000 metres, is not colder than the ground. This circumstance explains in full the incompetence of the carbonic acid to protect the ground from being cooled by radiation to a very low temperature in this instance. But if the quantity of carbonic acid were sufficiently increased, it would be able to prevent in most cases the formation of those winter anticyclones generated nowadays over certain arctic and northern regions. Instead of the anticyclonic winter cold, we should then have there a prevailing cyclonic weather—equal to the present common winter weather on the western coast of Europe. The winds would constantly transport warmer air from more southerly districts to the Arctic Regions; the sky would be cloudy, thus effectively hindering the radiation into space; and no noticeable inversion of temperature would occur. Under these circumstances then the protecting influence of the carbonic acid would act with its full power, and we should have a mild winter climate even in the Arctic Regions.

An interesting circumstance is here to be borne in mind. As long as the protecting power of the carbonic acid is strong enough to prevent the formation of the anticyclonic weather generated by a permanent cooling of the ground over large districts and the temperature inversion in the lower atmospheric strata resulting from it, the protecting influence of the carbonic acid will be greatest in the regions, daytimes, and seasons which are least favoured by nature; thus greatest at the pole, and from it decreasing towards the equator, greater during winter and night than during summer and day. Briefly, a sufficient quantity of carbonic acid will produce not only a warm climate, but also a uniform one over the whole earth. An inverse action will, of course, be produced by want of carbonic acid; thus not only a general fall of temperature, but also strong climatic contrasts between the different climatic zones and seasons.

The opinion that the genial climate of older geological ages was due to a greater quantity of carbonic acid in the atmosphere than the present one is by no means new. On the contrary, it was common among older geologists. But as the opinion then still was in want of support from physical facts, it was but an unproved conjecture. And as so enormously great a protecting power of the carbonic acid as we have found it to be was not suspected, it was thought necessary to assume a very high rate of carbonic acid in the atmosphere of ancient times in order to explain its genial and uniform climate. But as such a rate would have been fatal to all higher animal life, that objection was fatal to the hypothesis.[1] Further, those elder geologists believed it to be necessary for their explanation also to assume that the sky of those ancient times was much more cloudy than the present one, and besides that the inner heat of the earth contributed to the high temperature of the atmosphere. The last supposition is, as shown above, quite untenable.

[1] Eug. Dubois, *l.c.* p. 166, tells us positively: "The supposition of a formerly greater amount of carbonic acid in the atmosphere can now no longer be seriously discussed"; and this statement is considered to need no proof (!).

As to the question about cloudiness during different geological ages, there is no reason at all to believe that the sky of the genial periods was on an average more cloudy than the present one, but rather the contrary. For the more cloudy the sky is, the lower is generally the mean temperature of the air. Also the meteorological observations show that the amount of clouds on the whole increases from the equator to the pole, and does so though the rainfall decreases. But the amount of clouds has also a daily and a yearly period which play a very great part for the temperature. As a rule, the sky during the day is a little more cloudy than during the night, which, of course, enfeebles the insolation and reinforces the nocturnal radiation, thus lowering the temperature. The same may generally have been the case in the climates of ancient times. But as for the yearly period of cloudiness, the state is more variable. The climate of Western and North-Western Europe is characterised by the fact that the sky is much more cloudy during winter than during summer, and this is a cause which acts powerfully in producing the favourable climate of this region with its sufficient summer heat and moderate winter cold. But there are other regions on the earth where the inverse state prevails; the winter sky being as a rule rather unclouded, whereas a covered sky and frequent fogs characterise the summer weather. This is particularly the case in the polar regions, where the cold sea, filled with melting ice, seems to be the cause of the foggy and cloudy weather during the middle summer season. Again, there are other regions where the winter sky is nearly continually clear, and as a consequence the winter cold severe, but also the summer sky generally so cloudless that the insolation suffices to produce summer heat. This is the case in the interior of the great continents even north of the Arctic Circle.

Now, if we ask what was the yearly period of the cloudiness in the Arctic Regions during the Cretaceous age, when a nearly tropical climate prevailed there, the answer will be that probably the period was such as it is in Western Europe nowadays, *i.e.* that the summer sky was relatively cloudless and the winter sky relatively cloudy. For there can be no doubt that the polar regions were then washed by a lukewarm sea completely free from ice, just as now the Iberian Peninsula, France, and the British Isles. We may thus with a great probability assume that the beneficial climatic influence of the carbonic acid for the polar regions will be extraordinarily increased as soon as the quantity of it in the atmosphere has become great enough to prevent the formation of ice on the polar sea during the winter. If we imagine of what kind the polar night would be on an island which, like Ireland, was situated in the middle of a lukewarm sea and under a sky mostly covered, we cannot doubt that even with the present rate of carbonic acid in the atmosphere such an island would have a relatively high winter temperature. Even in Spitzbergen, which has a relatively clear winter sky and is surrounded by a sea partly covered with ice, the midwinter temperature is at present, owing to the influence of the warm Atlantic continuations of the Gulf Stream, higher than in the northern centre of cold of the Scandinavian Peninsula.[1] If the hypothetical polar island,

[1] According to my isothermal chart of Europe (*Ymer*, 1899, *l.c.*) the mean January temperature reduced to sea-level is − 16° C. in this centre (about 69° N. and 25° E. fr. Gr.),

holds good for the carbonic acid which animals exhale or which is formed by the putrefaction of bodies of animals; for this comes, without exception, from the plants which have served as food for the animals.

What enormous quantities of carbonic acid passed through the atmosphere during ancient times is best shown by the thick layers of limestone and chalk which are to be found in several geological formations, and which contain many thousand times as much carbonic acid as the present store of the atmosphere.[1] The quantities of carbon which are stored up as pit-coal, brown-coal, and turf mosses are certainly not so great, but nevertheless are gigantic.

We may thus say that the carbonic acid trade of nature is carried on with a very little capital and a very great exchange, in which, moreover, chance plays a considerable part. Hence it follows necessarily that great fluctuations in the capital stock will occur, so that sometimes abundance and sometimes want arises in the carbonic acid market. And if a reserve fund did not exist, it is to be feared that severe crises would occur now and then, which, from abundance or want of carbonic acid, and hence of heat, might be fatal to all life on the earth. This reserve fund lies in the carbonic acid stored up in the oceans. For sea water is capable of storing up a great amount of carbonic acid partly as a solution and partly as a loose chemical combination in the bicarbonates.[2] Arrhenius calculates that if six parts of carbonic acid be supplied to the air, five of them will go down in the ocean and only one remain in the air. Chamberlin takes into consideration a further circumstance of great importance, viz. the activity of limestone-secreting organisms. According to him, the total store of carbonic acid existing in the ocean in solution and in a loose chemical combination amounts to eighteen times as much as that in the atmosphere; by the activity of the limestone-secreting organisms, the loosely combined carbonic acid is set free and is partly given back to the atmosphere. Consequently if during a period of unusually lively volcanic activity on the earth the atmosphere receives a great supply of carbonic acid, most of it is stored up in the ocean—in part directly by absorption, in part indirectly by the weathered detritus transported by the rivers to the ocean. Out of this stored provision a part is gradually precipitated in form of calcium carbonate, but the rest is gradually given back to the air, especially if the quantity of carbonic acid in the atmosphere is diminished.

5. *The secular cooling of the earth is the principal cause of the variation of the quantity of carbonic acid in the atmosphere—Modifying influences.*

The principal cause of the secular or long-period variations of the quantity of carbonic acid in the atmosphere is to be found in the secular cooling of the earth, as will now be shown.

[1] A. G. Högbom, *l.c.*, calculates the store of carbonic acid in the stratified rocks to be 25,000 times that in the air, assuming the mean thickness of these strata to be 100 metres over the whole surface of the earth, which is probably a minimum value.

[2] S. Arrhenius, *Nordisk Tidskrift*, 1896, pp. 129-130; and J. C. Chamberlin, *l.c.* p. 611 and following.

We have already shown[1] that during the primeval time, when the whole crust was covered by the ocean, the crust contracted more than the inner nucleus, and that thereby a lively volcanic activity was produced—a state which probably continued many million years during the Pre-cambrian time. Further, we explained there how gradually an inverse state arose, during which the nucleus contracted relatively to the crust so as to form crumples on the crust, and this was the beginning of the first great mountains and continents. The explanation, however, there given of the formation of mountains and continents was incomplete; for we must consider one more important circumstance, viz. the influence of the carbonic acid on the temperature of the ocean and the air. For as the volcanic activity during the primeval time, as long as the crust contracted more than the nucleus, was singularly strong, the supply of carbonic acid to the ocean and the air was considerable. And as nearly all the ground was covered by sea, and the vegetable life but

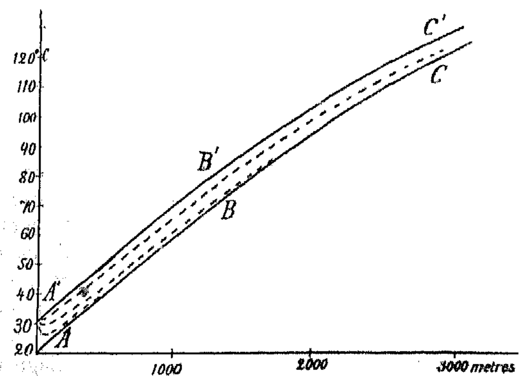

Fig. 1.

little developed, the consumption of carbonic acid by weathering of silicates and by organic processes was insignificant. Accordingly, the quantity of carbonic acid increased continually, and, by consequence, the temperature of the air, then that of the ocean, and further that of the ground and of the sea bottom, gradually rose. And if simultaneously also the intensity of the insolation increased, which is not improbable,[2] that rise of temperature was still greater. We shall now see what was the influence of this on the crust. Suppose, for instance, that the mean temperature of the ground (= sea bottom) was 20° C. during the primeval time, but gradually rose to 30° C.[3] Fig. 1 gives a graphic representation of the increase of the temperature in the earth with depth. According to the known laws of the conduction of heat, the temperature at different depths is represented by the faintly bent curve ABC, as long as the temperature remains constant at 20° C.[4] But if the mean temperature of the air is raised to 30° C. and main-

[1] Chapter 1, pp. 5 and 6.

[2] Op. chapter 3, p. 17.

[3] We have already seen that a relatively little increase of the quantity of carbonic acid in the atmosphere is sufficient to produce an increase of temperature equal to 10° C.

[4] The yearly and other variations of short period do not sensibly alter the regular course of the curve, for they penetrate only to a depth of a few metres.

tained at this degree during millions of years, then firstly the ocean is warmed, secondly heat penetrates from it and from the air into the earth's crust, and simultaneously the conduction of heat from the interior of the earth is going on invariably in the deeper layers. At first the temperature is speedily raised in the uppermost layers owing to the supply of heat from above (the dotted lines are intended to indicate this), then a very slow rise of temperature is going on, owing to the supply of heat from below, and this extends to depths which are always increasing, until the curve A'B'C', representing the new distribution of temperature, has become nearly parallel to the former curve ABC, but at a depth of several kilometres.[1] Consequently then the temperature of the crust has been raised relatively to the nucleus by about 10° C. What this signifies is shown by a simple calculation. The coefficient of linear thermal expansion of the crust may be assumed to be 0·00002 per 1° centigrade; and as the circumference of the earth is 40,000 kilometres, the whole circumference is lengthened by $10 \times 0{\cdot}00002 \times 40{,}000 = 8$ kilometres. But as the crust is not strong enough to break loose from the nucleus, it must bend and crumple itself in order to find room. If only one fold were formed at the end of the period of expansion, it would have a height of nearly four kilometres, which would be as high as the tops of the Alps. To this comes, moreover, the surplus already pointed out depending on the slow cooling of the nucleus. Moreover, as is proved by the geological facts, the effect of such a slow expansion is in reality enormously greater than the above calculation seems to indicate. For as soon as the expansion of the crust has been great enough to produce a crumple in it, this generally splits and the fissures formed are filled with eruptive magma, which is pressed up as wedges. Also the cavity formed under the crest of the crumple will be filled with such a magma. Thereby the crust will increase still more in length, thickness, and rigidity, whereas the nucleus will diminish in volume, so much the more as a part of the magma will often rise and spread over the surface of the crust. After some time a new crumple will be formed, and the same process will be repeated, and so on. Thus the above result found by Hein (see p. 8) ought to be explained.

In this manner the first great mountains and continents rose from the ocean. But as the chemical processes by which carbonic acid is consumed, both in inorganic and in organic nature, are strongly accelerated by a high temperature and also directly by an increase of carbonic acid, and as the land areas where these processes were going

[1] The depth at which the amplitude of a periodical variation of the surface temperature is reduced in a given rate being proportional to the square root of the length of the period, and the amplitude of the yearly period being reduced to the half at a depth of 2 to 4 metres (varying with the conductivity of the ground), we find the following lengths of the period corresponding to depths, at which the amplitude is reduced to the half of its value at the surface :—

Length of period.	Depth in metres.
1 million years	2000 to 4000
4 „ „	4000 to 8000
9 „ „	6000 to 12000
16 „ „	8000 to 16000

a. s. o.

A. J. Ångström, "Mémoire sur la température de la terre à différentes profondeurs à Upsal, Upsal, 1851," *Acta Reg. Soc. Sc. Upsaliensis*, Sér. 3, vol. i. pp. 147-224, Upsaliæ, 1855.

on had a very great extension compared with that of the former age, the consumption of carbonic acid was now increased to so high a degree that the quantity of it contained in the air became at first stationary and then began slowly to diminish. But during long times this diminution was prevented by the influence of the oceans. For by the denudation and erosion of water a great many carbonates, etc., were transported to the oceans, which thereby provided a richer food than before to the lime-shell animals. By the vital processes of these animals great quantities of carbonic acid were gradually set free and given back to the atmosphere as explained above, according to the theory of Chamberlin. Hence the temperature of the genial period was still raised and its duration lengthened. But as the ocean gives back to the atmosphere only a part of the carbonic acid consumed by the chemical processes, whilst the rest is precipitated in the form of stratified layers of limestone, a time must have come when the provision stored

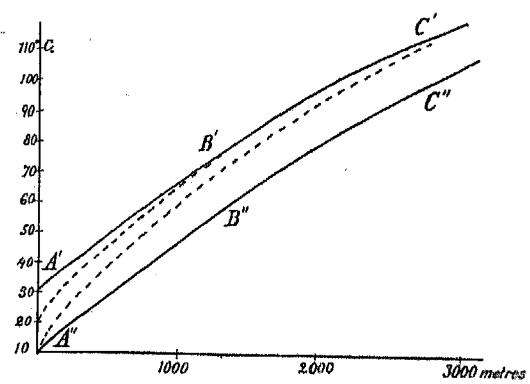

FIG. 2.

up in the ocean was consumed, and then the quantity of carbonic acid in the air gradually diminished. By consequence, also, the temperature of the air became first constant and then began slowly to fall. As a consequence, the cooling and contracting of the earth were going on, during a long time, at the same rate both in the crust and the nucleus. Thus a state of rest arose in the volcanic activity, and accordingly in the production of carbonic acid, and the temperature fell more and more and the climate deteriorated.

But the relatively low temperature which now ruled during long ages exercised two influences which gradually increased the rate of carbonic acid again, and thereby raised the temperature of the air, ocean, and ground.

Firstly, the consumption of carbonic acid for weathering silicates and for other chemical processes, both in inorganic and organic nature, was considerably diminished owing to the low temperature.

Secondly, the volcanic activity was increased, which caused an increased production of carbonic acid. In order to understand this, let us consider Fig. 2 (cf. Fig. 1), and suppose that the mean temperature has fallen from 30° to 20°, and then further from that to 10° C.[1] Now let the curve A'B'C' represent the distribution of the temperature at different depths towards the end of the genial period, when the mean temperature of the earth's surface was still 30° C. As soon as this has fallen to 20° C., the heat of the crust is rapidly going away from the uppermost layers to the surface and radiating away from it. Thereby the geothermal gradient is gradually increased, and, of course, also the loss of heat by conduction; and this will go on to continually deeper layers, until the distribution of temperature will be such as that indicated by the dotted line beginning at 20° C. at the surface. Further, as soon as the mean temperature of the surface has fallen to 10° C., the heat is conducted still faster away from the crust, and the distribution of the temperature after some time will be that indicated by the dotted line beginning at 10° C. in the surface. If this low temperature continues long enough, the heat of the earth is carried off from always deeper layers, and finally the distribution of the temperature will be that indicated by the curve A"B"C", which, still at a depth of several kilometres, is running nearly parallel to A'B'C'. Thus the mean temperature of the crust has fallen by not less than 20° C. in a relatively short geological period. In the same time the nucleus has been cooled only very little, at the most 1° or 2° C., and thus, principally owing to the diminution of the quantity of carbonic acid in the atmosphere, a relative fall of temperature amounting to nearly 20° C. has taken place in the crust. A contraction is thereby produced in this relatively to the nucleus, the amount of which may be easily calculated if we know the coefficients of thermal linear expansion for the crust and for the nucleus. For the former we assume, as above, this coefficient to be 0·00002, for the latter we may suppose it to be twice as great, or 0·00004, and accordingly the relative contraction of the crust will be at least $20 \times 0{\cdot}00002 \times 40{,}000 - 2 \times 0{\cdot}00004 \times 40{,}000 = 12{\cdot}8$ kilometres on the whole circumference of the earth. Evidently, as long as this contraction is going on, a great many fissures and subsidences in the regions formerly crumpled, with accompanying volcanic eruptions, will occur. But thereby a genial geological period is again inaugurated. This, of course, just as the former periods, will then have its progress, culmination, and decadence, owing to the repetition in nature of nearly the same influences as before, and this will go on as long as the interior of the earth is hot enough to maintain volcanic activity.

Thus during the whole geological interval a periodical variation in the mean temperature of the atmosphere, the ocean, and the upper crust of the earth has been going on, as shown by the above reasoning, which is based exclusively on physical arguments. It is evident that the length of such a period will be considerable, and will probably amount to many million years; but this theory, of course, is unable to determine its mean length.

It now remains also to prove the existence of this variation by means of purely geological facts; but before doing this we shall consider two more physical circumstances which will noticeably modify the variation.

[1] This is not more than the probable fall of temperature from the Cretaceous to the Pleistocene period.

The one is the continual erosion and denudation of the continents by means of rain. Its effect will be very complicated; for on the one hand it uncovers the rocks for the weathering process and thus reinforces the consumption of carbonic acid, but on the other hand it transfers, directly or indirectly, the surface of the earth to the sea, where it is covered by water and thus protected from weathering. Probably the latter effect is stronger, and thus, the weathering being much more active during the warm periods than during the cold ones, the result will be that the warm periods are much strengthened and lengthened and the cold ones enfeebled and shortened. Also the erosion and denudation is very important for life on land and in sea, and thereby may exercise a marked influence of a very complicated nature. I cannot enter on this question, which has been elaborately discussed by Chamberlin.[1]

The other modifying circumstance is the influence of the great oceans on the temperature on the earth's surface.

As we know, the ocean, nowadays, covers the greater part of the earth's surface, and there can be no doubt that this has always been so. But out of the heat that the ocean receives from the sun and the air, only a little part penetrates to its bottom. For as a rule the heated water is more buoyant than the underlying colder layers, and thus is floating above. Only exceptionally does it happen that the warmer water sinks down owing to its greater saltness. The slow motions in the oceans caused by the differences of temperature are at present such that the ice-cold water at the poles is sinking down, and spreads on the bottom of all deep seas which communicate with the polar basins. Owing to this, the temperature of the sea bottom is at present nearly constant, and about the freezing-point or a little below. This has evidently been so since the Great Ice Age. The rise of the mean temperature of the air, amounting to about 5° C., which has taken place since the Ice Age, has thus only come to benefit the crust in a small degree.

Something similar must also hold good for earlier geological ages. For even during the periods when the polar regions enjoyed a temperate or genial climate, the mean temperature there must nevertheless have been lower than nearer to the equator, though the difference ought then to have been less than during the colder periods. And if the deep oceans always have communicated at least with one of the polar basins, —which I believe was the case,—we must conclude, according to the laws of physics, that the mean temperature of the bottom of the ocean has always depended on the temperature of the surface of the polar basins, where the coldest water sank to the bottom.

Hence it can only have been during the hottest periods of all that the expansion of the crust, owing to heating from above, became so considerable that great mountains and continents were lifted up from the ocean. Furthermore, it is evident that the calottes of the crust which surround the poles ought to have got, on account of the stronger cooling, a greater rigidity than the other parts of the crust, where the cooling will, on the whole, have been feebler. In consequence, the polar calottes have been less crumpled than the other parts of the crust, and no large

[1] T. C. Chamberlin, *l.c.* p. 616 and following.

and mountainous polar continent has probably ever existed, unless, perhaps, during the primeval or Archæan era.[1]

It also follows from the above that an increase of the mean temperature of the atmosphere is only slowly and partly communicated to the bottom of the ocean, and from hence to the crust, whereas a decrease is rapidly and in an exaggerated scale propagated to it. Now we have seen that every heating of the crust produces effects that tend to increase the consumption of carbonic acid, and accordingly to cool the atmosphere. Thus the ocean, by protecting the crust from being heated from above, has the effect of prolonging an age of genial climate. On the other hand, as every cooling of the crust produces effects that tend to rapidly augment the production of carbonic acid and thereby to warm the atmosphere, it results that the ocean, by accelerating the cooling of the crust by means of ice-cold water, has also the effect of shortening considerably the length of a cold geological period. Thus we are led to the conclusion that the geological periods of an intense cold have constituted only a very short time in comparison with the periods of a genial climate.

We will now compare the above theory with the testimony of geological facts.

First, then, I shall remark that the explanation given above of the principal cause of volcanic activity and formation of mountains and continents fully agrees with the views of modern geologists, as far as I have been able to judge.[2] And I think that some of the difficulties hitherto felt in the explanations of the facts observed will be removed by applying the above theory to these facts.

Firstly, the geological history of the earth gives evident proofs that both the volcanic activity, the formation of continents and mountain ranges, and the climate during the geological past have undergone such a periodical variation as I have deduced from a purely physical reasoning. And these proofs are more evident the more fully we know the geological facts.[3]

Of what has passed on the earth during the Archæan era and the older periods of the Palæozoic era we know too little to be able to make a comparison. We can only say that there is nothing to be found in the facts now known that disproves our theory.

But after that time there are positive facts enabling us to make a comparison. Thus, according to Frech,[4] we may distinguish during the history of the earth two periods during which a mountain formation embracing the whole globe has occurred, viz. the younger Palæozoic (Carboniferous) and the second half of the Cainozoic era (after the Oligocene),

[1] If the angular velocity of the earth in its rotation has been noticeably retarded by tidal friction, and as a consequence of it the earth has gradually taken a more spherical form during geological time,—which is very probable,—the same effect will have been produced thereby, viz. the crumplings of the crust accompanied by fissures nearer the equator, and the forming of fissures without crumpling in the vicinity of the poles.

[2] See, for instance, the treatise by Neumayer and Uhlig cited above.

[3] Sir Archibald Geikie, *Text-Book of Geology*, 2nd ed., London, 1885, p. 22, says: "As evidence has accumulated in favour of periodic alternations of climate, the conviction has been strengthened that no mere local changes could have sufficed, but that secular variations in climate must be assigned to some general and probably recurring cause." (The last edition was not accessible to me.)

[4] Fritz Frech, "Ueber die Gebirgsbildung im paläozoischen Zeitalter," *Geographische Zeitschrift*, Jahrg. V. 1899, p. 563 and following.

whereas the Mesozoic and the beginning of the Cainozoic era were generally times of deep immobility. According to Neumayer and Uhlig,[1] we may likewise distinguish a Pre-permian and a Tertiary period of general activity of mountain formation, which are separated by a long period of rest, during which no crumplings and only few volcanic eruptions occurred, whereas the immersion of land in the ocean increased, and stratified deposits were continually formed. But these authors put the beginning of the later period of activity somewhat earlier than Frech, viz. in the upper Cretaceous, though the principal crumpling occurred later, and was going on with interruptions till the Pliocene.

Now both these active periods constitute the later part of a very warm period, and the transition from it to a very cold one. During the warm period we find a luxuriant vegetation, during the cold one a poor vegetation and a glaciation of large regions of the ground. As to the elder of these periods, the Permo-Carboniferous, the facts are less reliable; but, according to the opinion of most geologists, it ended with a cold age, which approximately falls in with the Permian period. The rich flora of the Carboniferous period was then partly extinct, and a check in the vegetation occurred. Also a glaciation of large regions, comparable with that following the Tertiary period, occurred. The traces of this glaciation have been found principally in the southern hemisphere, where a great continent existed at that time, and may be partly explained by the height of the land. But its existence and great extension seem to be acknowledged as a fact by nearly all geologists. But it did not last long, geologically speaking; for after it occurred the Mesozoic era, which seems to have enjoyed an invariably genial climate. This long warm age culminated during the Cretaceous and Eocene periods, when the vegetation again reached a luxuriance comparable with that of the Carboniferous era. But then a great activity in the formation of mountains and continents set in, and as a consequence we see a gradual deterioration of the climate, commencing just as after the culmination of the Carboniferous warmth. The temperature is now falling rapidly,—geologically speaking,—and at last the Great Ice Age breaks in. As to this, there is no doubt about its existence and extension. For it has left traces all over the globe, and they prove that the lowering of the temperature was general. The snow-line is found to have been lowered everywhere on the earth by about 1000 metres, indicating a temperature about 4° or 5° C. lower than the present one. But the cold period was but short compared with the enormously long genial age previous to it. And the cold was not continual. For it was interrupted by at least two or three temperate inter-glacial ages, during which the climate was even somewhat milder than at present. Some geologists count up to six inter-glacial periods. Some of these may have been only local, consisting in a melting away of the southern borders of the ice by a rise of the summer temperature owing to the astronomical cause considered in the next chapter. But the great and general inter-glacial periods of the Pleistocene cannot be explained thus. They no doubt depend on the same cause as the long-period changes above discussed—that is to say, on a variation in the quantity of carbonic acid of the atmosphere. I shall now show that these periodical variations during the Pleistocene were

[1] Neumayer and Uhlig, *l.c.* p. 357 and following.

probably caused by the modifying influences pointed out above, viz. the erosion and denudation of the land by water and ice, and the influence of the ocean on the temperature of the upper crust. Of these two influences, the latter was no doubt the far more effective, and therefore we shall consider it first.

During the hottest period, Cretaceous and elder Cainozoic, the crust was heated, and thus expanded relatively to the nucleus. But the heating and expansion were by no means uniform, for the continents were heated much more than the sea bottom. Moreover, this had generally a greater rigidity than the land, as it had been cooled by the water. The consequence was that the crust was crumpled principally along the coasts[1] and in the warmer regions of the earth. Very instructive in this respect is the account which Suess gives of the extension of the young mountain ranges. We see from it how the wrinkle caused by the relative expansion of the crust runs from the south-west point of Europe eastward over the south of Asia to the East Indian Islands, then north-eastward along the east coast of Asia up to Kamtschatka, and from that turns in a sweep southwards over to North America and farther along the west coast of this continent, whence it turns in another sweep to the east over the West Indian Islands to the north end of South America, and finally along the west coast of it down to Cape Horn and perhaps on as far as Graham Land. Thus we see that the crust has closed up both in a north-southerly and east-westerly direction, but principally in the warmer regions of the earth by means of a crumple running along the coasts.

Now as soon as the temperature had fallen enough to produce a glaciation of the polar regions, the sea bottom was rapidly cooled by ice-cold water, whereas the continents at a greater distance from the poles were still relatively warm. In consequence, the sea bottom contracted, and the fissures at the borders of the young mountain ranges along the coasts were opened so as to produce vertical faults with subsidence of large regions along the feet of the mountain ranges. Thereby arose a very lively volcanic activity, producing a range of volcanoes and volcanic eruptions along the new mountain range, and also in several other places. This is shown very strikingly by the chart given by Neumayer and Uhlig.[2] This volcanic activity is said to have been very lively during the whole Pleistocene period, and there can be no doubt that it culminated during the periods of glaciation. Thereby was produced a great quantity of carbonic acid, and at the same time the consumption of it was considerably diminished, owing to the low temperature and the ice-covering of large regions. By consequence, the quantity of carbonic acid increased, and a temporary amelioration of the climate occurred, forming an inter-glacial period. This process may have been repeated several times.

During the inter-glacial periods, the upper crust of the land was somewhat heated, but their length was probably too short to produce an expansion sufficient for mountain formation, so much the more so

[1] Thereby I do not mean to say that a crumpling along the coasts is a general rule in the formation of mountains, but only that it probably is more common than the crumpling of the crust far from the coasts.

[2] Neumayer and Uhlig, *l.c.* p. 194, "Vertheilung der Vulkane auf der Erde."

as the temperature of the sea bottom remained constant at about the freezing-point during the whole Pleistocene era, and from that to the present time.

But during all this time erosion and denudation acted constantly to diminish the large surfaces of the mountains and continents formed during the end of the warm period. Simultaneously also large land areas were immersed under water, such as the Mediterranean, the Red Sea, the greatest part of Scandinavia and Finland, the regions south-east and east from Asia, the Caribbean Sea, etc. Thus, after some glaciations the consumption of carbonic acid must diminish so much that a permanent or at least very long amelioration must occur. But the end of the last glaciation occurred so recently that we cannot say if we now are living in an age of periodical glaciation or at the beginning of a genial period.

6. *Variations of the obliquity of the ecliptic, and their influence on the climate.*

After we have thus tried to explain the cause of the great climatic changes during the geological past, it remains to examine the smaller ones. Among these there is one that requires our special attention, because it very nearly concerns us. It is a climatic variation which has been shown to have happened during the Quaternary time, after the melting away of the ice in the northern countries, particularly in Scandinavia, Spitzbergen, and Greenland, and which no doubt is still passing on. It has been also, if not discovered, yet examined most accurately by Swedish botanists and geologists—F. W. C. Areschoug, S. Berggren, Th. Fries, A. G. Nathorst, Gunnar Andersson, H. Hedström, and others.

Already Berggren and Fries, but still more positively Nathorst,[1] conclude, from the phyto-geographical state of Spitzbergen, that there must once have been a time, after the present vegetation of Spitzbergen already had immigrated, or during which it was immigrating, when the climate was warmer than now. And proofs of the existence of such an age is also afforded by the geological evidence, which shows that there was an interval during the post-glacial period when the sea was warmer than at present, so that *Fucodium canaliculatum*, *Mytilus edulis*, *Cyprina islandica*, and *Litorina litorea* could live there, none of which nowadays is to be found in the Spitzbergen waters. Further, Nathorst remarks that signs of a milder climate during the post-glacial time may be found over nearly all the northern parts of our hemisphere—Scandinavia, Iceland, Greenland, North America, etc. This was indeed indicated already in 1866 by Areschoug concerning Scandinavia, for the reason that certain plants, as *Trapa natans*, *Ilex*, *Acer campestre*, etc., had formerly wider northward dissemination than now. Also British authorities, as J. Geikie and J. D. Hooker, have arrived at the same result. So far

[1] A. G. Nathorst, "Nya bidrag till kännedomen om Spetsbergens kärlväxter och dess växtgeografiska förhållanden" ("New Contributions to the Knowledge of the Vascular Plants of Spitzbergen and its Phyto-Geographical State"), Stockholm, 1883, *K. Sv. Vet. Ak. Handl.* Bd. 20, No. 6, p. 63 and following pages.

Nathorst. It may be remarked that already Ehrenheim,[1] in 1824, tells us, as a proof of the deterioration of the climate in later times, that wood formerly grew in the northernmost part of Norway long above the present wood limit.

Gunnar Andersson,[2] on the basis of the history of the Swedish vegetation, has given a general description of what is at present known about the climate of Sweden during the Quaternary Age. Later he has in the same way studied the climate of Finland also. After the melting away of the ice the temperature gradually rose, and a steadily increasing flora immigrated. First came an arctic vegetation, the Dryas flora, with Dryas, arctic willow, and dwarf birch; later came the flora of the common birch, then that of the fir, and at last that of the oak. The latest indicates the warmest time of the Quaternary climate. The oak grew then farther to the north than now, and formed real forests as well in Southern and Middle Sweden as in Southern Finland, and the hazel (*Corylus avellana*) throve in Southern Norrland north of the 63rd latitude.[3] Simultaneously the water-calthrop (*Trapa natans*) throve and ripened its fruit in the lakes of Southern and Middle Sweden and Southern Finland. Andersson has also tried to determine approximately the millenary of our era, when this warm climate occurred. The oldest known traces of the existence of man within the limits of Scandinavia first inhabited descend to the middle or later part of the Oak Age, and these men belonged to the elder Neolithic Stone Age, who did not know the use of sharpened flint. Now as, according to Oscar Montelius, the Bronze Age of Sweden began at latest about 1700 years B.C., and Andersson estimates the duration of the Stone Age in our country as at least equally as long time as that which has elapsed from the beginning of the Bronze Age to our time, and perhaps some one or more thousand years longer, thus man has lived in Sweden for at least 7000 years, and perhaps some one or more thousand years longer. The time of the warmest climate in the northern countries accordingly occurred some 10,000 to 7000 years ago. But after that time the climate has again gradually deteriorated, and, as we shall see, the deterioration is still going on. The water-calthrop, for want of summer heat, has become completely extinct in Finland and also in Sweden, and is now to be found only in a single lake in Scania; this plant is said now to thrive well only in South Europe. The oak, hazel, etc., have retired backwards to the south, partly for want of summer heat, partly owing to the struggle with other trees and shrubs requiring less heat.

[1] Ehrenheim, "Om Climaternes rörlighet" ("On the Variability of the Climates"), *K. Vet. Ak. Stockholm*, 1824, p. 178: "In our newspapers for 1817 we have read a letter from Wadsö, where they complained that the climate of later times has become harder; the wood becomes extinct; the line for forest growth is going downwards from the heights; where trees are dying new ones do not come up; in the turf mosses in the Alps one finds tree stems and roots where no trees are now growing."

[2] Gunnar Andersson, *Svenska växtverldens historia*, 2dra uppl., Stockholm, 1896, p. 82 and following ("The History of the Swedish Vegetation," 2nd ed.); "Studier öfver Finlands torfmossar och fossila kvartärflora" ("Studies on the Turf Mosses and Fossil Quaternary Flora of Finland"), *Bulletin de la Commission géologique de Finlande*, No. 8, Helsingfors, 1898.

[3] See also H. Hedström, "Om hasselns forntida och nutida utbredning i Sverige" ("On the Former and Present Extension of the Hazel in Sweden"), *Geol. Fören. Förhandl.* Bd. 15, 1893. Hedström concludes that the time of this milder climate falls at and nearest after the maximal extension of the Litorina Sea.

Comparing the former and present northern limits of the hazel with the position of the mean isotherms for the year, Andersson finds a decrease of about 2° C. in the average yearly temperature of Northern and Middle Sweden from the warmest time of the Oak Age to the present time.

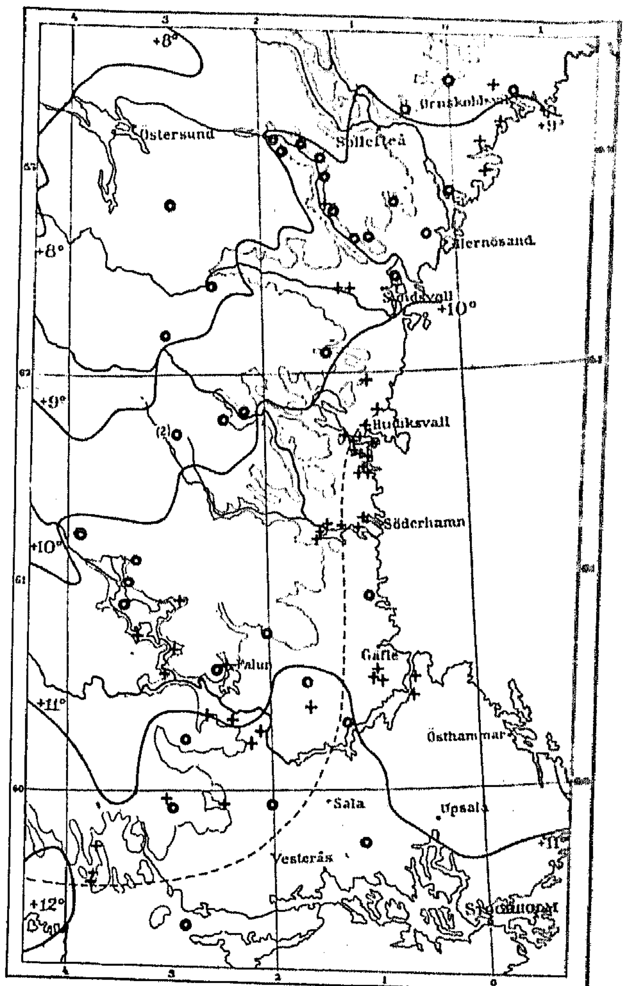

FIG. 3.—Map showing the occurrence of the hazel as Fossil (o) and Living (+) in Middle and North Sweden, according to Gunnar Andersson. The thick continuous lines designate the isotherms of the Summer half of the Year (April to September inclusive) on an average for 1860-1894. They are true isotherms, not reduced to sea-level. The dotted line indicates the present northern limit of a more frequent occurrence of the hazel (also according to Gunnar Andersson). The thin continuous line represents the curve of a height of 200 metres above sea-level.

As we shall see, there is, however, no reason to believe that the temperature of the winter half of the year has been sensibly different now from what it was then. And, in fact, the flora of so northern a country as Sweden cannot give any trustworthy evidence for judging of any little variation in the winter temperature. If we consider the isotherms only for the summer half of the year, we find likewise a decrease of temperature amounting to about $1\frac{1}{2}°$ to 2° C. from the warmest time of the Oak Age up to our time.[1] This is illustrated by the accompanying chart, Fig. 3.

I shall now show that all this Quaternary variation of climate may be simply and completely explained by means of the long-period variations in the obliquity of the ecliptic, *i.e.* the dihedral angle between the planes of the equator and the earth's orbit. The most reliable calculation of this is considered to be that made by J. N. Stockwell.[2] I have tabulated the formula given by him[3] from 100,000 years before down to 50,000 years after our time, and therefrom drawn the curve shown in Fig. 4. According to the formula, the mean value of the obliquity

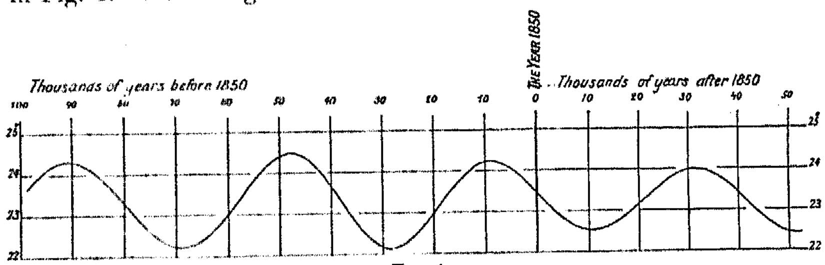

FIG. 4.

is equal to 23°·288, the greatest 24°·600, and the least 21°·977. But the greatest and least values which occur during the above-named time of 150,000 years are found to be:—

Year.	Maximum.	Year.	Minimum.
−91,014	24°·31	−68,759	22°·22
−48,022	24·47	−28,296	22·13
− 9,076	24·24	+10,144	22·53
+31,387	24·01	+51,618	22·42

where the years are reckoned from 1850 backward (−) and forward (+).

[1] It is not impossible that the Polar tribes lived farther to the north during the warm time 9000 years ago than nowadays. According to Kurt Hassert ("Die Nordpolar-Grenze der bewohnten und bewohnbaren Erde," *Petermann's Mittheilungen*, 37 Bd., 1891, p. 141, Chart: Tafel 11), the Esquimaux once lived much farther to the north than now in the Arctic Archipelago of North America and in Greenland, viz. north of the 75th latitude, and at Kennedy's Channel between Grant Land and Greenland even up to 82° N. Also the islands of New Siberia were once inhabited. We know nothing else, however, about the date for this. See also the next chapter, p. 51, the first note.

[2] J. N. Stockwell, "Memoir on the Secular Variations of the Elements of the Orbits of the Eight Principal Planets," etc., *Smithsonian Contributions to Knowledge*, vol. xviii., Washington, 1873.

[3] J. N. Stockwell, *l.c.* p. 174. For my purpose I have put the formula in the following simplified form:—

$$\begin{aligned} e = 23{\cdot}288 &- 0{\cdot}806 \cos(0{\cdot}008\,897\,04t + 251{\cdot}75) \\ &- 0{\cdot}210 \cos(0{\cdot}009\,179\,13t + 292{\cdot}83) \\ &+ 0{\cdot}165 \cos(0{\cdot}006\,806\,58t + 306{\cdot}32) \\ &- 0{\cdot}069 \cos(0{\cdot}012\,586\,71t + 21{\cdot}11) \\ &+ 0{\cdot}054 \cos(0{\cdot}012\,179\,48t + 132{\cdot}68) \\ &- 0{\cdot}006 \cos(0{\cdot}013\,200\,60t + 133{\cdot}94) \\ &- 0{\cdot}001 \cos(0{\cdot}013\,826\,83t + 20{\cdot}52) \end{aligned}$$

where e signifies the obliquity at t Julian years after 1850, and all the numerical coefficients are expressed in degrees and decimals of a degree.

But the greater this angle is, the warmer, and the less it is, the cooler, will be the summer of the northern countries, and that for two reasons. When, for instance, the angle has its maximum, the polar circle arrives at its southernmost position, and by consequence both the time during which the sun is above the horizon in summer attains its greatest length, and also the sun its greatest height in the sky, and both these circumstances increase the summer heat. The inverse will be the case when the angle has its least value. Thus a periodic variation of the climate occurs, the length of the period being about 40,000 years, and alternately warmer and cooler intervals of about 20,000 years result. The warmest epochs occurred, as will be seen from the above Table, or from the curve in Fig. 4, about 91,000, 48,000 and 9000 years ago, and will occur after about 31,000 years, etc. It is obvious that the warm time 9000 years ago coincides with that calculated by Gunnar Andersson, when the warmest time of the Oak Age occurred. By a nearer inspection of the curve, it may be found that this warm time must have continued, with little variation, about from 11,000 to 7000 years before our time, and thus during about 4000 years; for the angle between the equator and the ecliptic has varied only little during these 4000 years. But since that time the angle has gradually decreased, which has caused a continual lowering of the summer temperature. This will continue still for 10,000 years, after which time this deterioration of climate will reach its culmination. From the table or the curve one may see that cold intervals occurred about 69,000 and 28,000 years ago, and will occur after 10,000 and 52,000 years.

The most interesting to us among these intervals are that with a low summer temperature which occurred 28,296 years before 1850, and that with a high summer temperature which occurred 9076 years before that year, because these must certainly have had influence on the climate of the Quaternary Age. We shall now examine how great this influence was. Firstly, as to the length of the time during which the sun is continually above the horizon about midsummer. I have calculated it for Karesuando, the most northern meteorological station of Sweden (68° 26′ N., 22° 30′ E. fr. Gr.).[1]

We find that this time lasted

from June 3 to	July 10	inclusive, *i.e.*	38	days,	28,300	years ago.
,, May 22 to	,, 22	,,	62	,,	9100	,,
,, May 26 to	,, 18	,,	54	,,	at present.	

It is obvious that so great a variation in the length of the time during which the sun is above the horizon cannot be without influence

[1] Let δ be the declination and α the right ascension of the sun, and ϵ the obliquity of the ecliptic, then we have

$$\tan \delta = \tan \epsilon \sin \alpha,$$

where, with a sufficient approximation, we may take for α the values published for any year in the *Nautical Almanac*. By this approximation we neglect the variations depending upon the secular variations in the eccentricity of the earth's orbit and in the longitude of its perihelion; but as the total amount of insolation is constant for a given angle of the ecliptic, an increase of intensity of insolation will always be compensated by a shortening of the duration, so that the result will be essentially the same as if the eccentricity and the longitude of perihelion were constant.

Let ϕ be the latitude of the station, and put 35′ for the horizontal refraction, then the sun will be continally above the horizon as long as

$$\delta > 90° - \phi - 35'.$$

on the temperature and the vegetation. Such a variation occurs in all latitudes, though, of course, it is not so great south of the Arctic Circle.

Further, in order to determine the influence on the temperature, I have, according to the methods indicated by Meech,[1] Wiener,[2] and Zenker,[3] calculated the relative intensity of the insolation for the 15th of every month, and for every 5th latitude in the northern hemisphere, during the three epochs in question,[4] and then, by taking the difference between the values for the two old epochs and those for the present time, calculated the overplus or the defect of insolation at these epochs compared with the present time.

In this manner I obtained the following Table III., p. 42 :—

In this Table the mean insolation falling on the earth in twenty-four hours is assumed to be 720 gram-calories per square centimetre, corresponding to a solar constant equal to 2. See Chapter 3, p. 19, and the foregoing note.

Further, as shown in Chapter 3, p. 19, by means of the differences in the Table I. and the mean temperatures of the parallels known from meteorological observations, I have calculated the differences from the present temperatures which correspond to those overpluses or defects of daily insolation. In this manner the following Table IV., p. 43, was obtained :—

As the differences of temperature given in the above Table are deduced only from the differences of insolation, they are valid, of course, only on the supposition that the differences of heat are consumed in heating the air and ground, and not in melting ice or snow and evaporating water, and that the absorbed solar heat benefits the place where it strikes, and is not carried by means of winds and ocean currents to other regions. Also, as the values are means for the parallel circles, and calculated irrespectively of the different quantities of clouds or transparency of the air, there may be local anomalies to be borne in mind in the application of the Table.

[1] Meech, "On the Relative Intensity of the Heat and Light of the Sun," etc., *Smithsonian Contributions to Knowledge*. Washington, 1856.

[2] Wiener, "Ueber die verhältnissmässige Bestrahlungsstärke," etc., *Schlömilch's Zeitschr. für Mathematik und Physik*, 1877, Th. 22.

[3] W. Zenker, *Die Vertheilung der Wärme auf der Erdoberfläche*. Berlin, 1888.

[4] Also in this calculation I have taken the right ascension α and the radius vector r of the earth from the *Nautical Almanac* (1883), thus considering the eccentricity and the longitude of perihelion as constants. This, for the reason above mentioned, introduces no error of practical importance. Assuming the cosine law for oblique rays, putting δ constant during a day, designating by H the half day-arc and by A′ the insolation in gram-calories per square centimetre for perpendicular rays during a true solar day of a length of t seconds mean solar time, when the radius vector of the earth r is expressed in its mean value as unity, we get, ϕ being the latitude,

$$\text{Sum of insolation during that day} = 2A'(\sin\phi \sin\delta \cdot H + \cos\phi \cos\delta \cdot \sin H).$$

Now if A designates the insolation in the same units as A′ during 24 hours = 86,400 seconds mean solar time, when the earth is at its mean distance from the sun, we have

$$A' = \frac{t}{86{,}400 r^2} \cdot A.$$

In order to be able to apply afterwards the method of calculation explained above (Chapter 3, page 19), I put now the absorbed insolation equal to $\frac{5}{8}$ of Langley's value, thus:— $A = 2 \times 1440$, and $A' = \frac{t}{30 r^2}$. Also the values of t have been taken from the *Nautical Almanac*.

TABLE III.—OVERPLUS (+) OR DEFECT (−) OF THE INSOLATION IN GRAM-CALORIES PER CM^2 IN TWENTY-FOUR HOURS COMPARED WITH RECENT INSOLATION (1883) FOR THE 15TH OF EVERY MONTH.

28,300 *years ago.*

Lat. N.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
°	°	°	°	°	°	°	°	°	°	°	°	°
90	0·0	0·0	0·0	−29·5	−50·0	−58·7	−56·4	−39·9	−9·4	0·0	0·0	0·0
85	0·0	0·0	+2·3	−29·4	−49·7	−58·5	−56·2	−39·7	−6·6	0·0	0·0	0·0
80	0·0	0·0	+3·0	−25·8	−49·1	−57·8	−55·5	−39·3	−6·0	+ 5·1	0·0	0·0
75	0·0	+ 7·2	+3·1	−19·9	−48·2	−56·7	−54·5	−32·7	−5·2	+ 8·5	0·0	0·0
70	+ 0·1	+11·5	+3·0	−17·3	−39·6	−55·1	−53·0	−26·9	−4·9	+ 9·5	+ 8·3	0·0
65	+12·6	+13·2	+3·0	−15·8	−31·7	−43·8	−39·4	−23·4	−4·4	+ 9·9	+13·7	+10·0
60	+16·9	+14·0	+2·9	−14·4	−27·4	−35·6	−32·4	−20·0	−4·2	+10·0	+16·4	+16·2
55	+18·9	+14·5	+2·9	−12·9	−23·7	−29·7	−27·6	−18·1	−4·0	+10·2	+17·5	+19·2
50	+19·6	+14·1	+2·7	−11·8	−20·0	−25·4	−24·2	−15·9	−3·5	+10·0	+18·1	+20·9
45	+19·8	+13·8	+2·3	−10·3	−17·2	−21·3	−20·8	−14·0	−3·0	+ 9·6	+18·4	+21·1
40	+20·0	+13·1	+2·0	− 9·3	−13·9	−17·4	−17·4	−12·0	−2·3	+ 8·8	+17·9	+21·5
35	+19·4	+12·4	+1·9	− 8·0	−11·8	−13·6	−14·1	−10·0	−2·0	+ 8·5	+17·1	+21·1
30	+18·7	+11·5	+1·9	− 6·7	− 8·1	−10·1	−11·0	− 7·7	−1·8	+ 7·3	+16·1	+20·2
25	+17·4	+10·3	+1·6	− 5·7	− 5·6	− 7·1	− 7·6	− 5·8	−1·2	+ 6·4	+14·6	+18·8
20	+15·9	+ 9·1	+1·3	− 3·9	− 3·1	− 3·0	− 4·7	− 3·6	−0·8	+ 5·2	+13·0	+17·5
15	+13·7	+ 7·9	+1·1	− 2·6	− 0·5	+ 0·3	− 1·0	− 1·8	−0·1	+ 4·0	+11·2	+15·7
10	+11·5	+ 6·5	+0·8	− 1·2	+ 1·5	+ 3·0	+ 2·0	+ 0·2	0·0	+ 3·2	+ 9·2	+13·3
5	+ 9·5	+ 4·6	+0·4	− 0·4	+ 3·6	+ 5·8	+ 4·5	+ 1·8	+0·1	+ 2·3	+ 7·5	+10·6
0	+ 7·1	+ 2·8	+0·2	+ 1·7	+ 5·1	+ 7·6	+ 6·7	+ 3·1	+0·2	+ 1·3	+ 5·6	+ 8·2

9100 *years ago.*

Lat. N.	Jan.	Feb.	Mar.	April.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
°	°	°	°	°	°	°	°	°	°	°	°	°
90	0·0	0·0	0·0	+17·4	+32·5	+35·4	+33·5	+24·7	+5·8	0·0	0·0	0·0
85	0·0	0·0	−1·2	+17·3	+32·4	+35·2	+33·4	+24·6	+3·9	0·0	0·0	0·0
80	0·0	0·0	−1·4	+16·5	+32·0	+34·8	+33·1	+24·4	+3·4	−2·7	0·0	0·0
75	0·0	−4·7	−1·5	+11·9	+31·4	+34·0	+32·4	+21·5	+3·1	−5·0	0·0	0·0
70	0·0	−6·8	−1·6	+10·5	+27·6	+32·6	+31·5	+16·9	+3·0	−5·8	− 3·8	0·0
65	− 6·9	−8·0	−1·7	+ 9·2	+21·4	+27·6	+25·6	+14·5	+2·9	−6·3	− 8·0	− 4·5
60	− 9·5	−8·6	−1·7	+ 8·0	+19·0	+22·1	+20·4	+13·1	+2·8	−6·3	− 9·9	− 9·0
55	−10·6	−8·7	−1·6	+ 7·0	+17·0	+18·5	+16·9	+11·8	+2·6	−6·2	−10·8	−11·0
50	−11·2	−8·3	−1·5	+ 6·5	+15·1	+15·0	+14·2	+10·5	+2·4	−6·0	−11·0	−12·2
45	−11·9	−8·0	−1·4	+ 5·7	+13·3	+12·2	+11·9	+ 9·1	+2·1	−5·7	−11·0	−13·0
40	−12·0	−7·6	−1·3	+ 4·8	+11·5	+ 9·8	+ 9·6	+ 8·0	+1·6	−5·3	−10·9	−13·0
35	−11·8	−7·1	−1·1	+ 4·0	+ 9·4	+ 7·7	+ 8·0	+ 6·8	+1·4	−5·0	−10·3	−12·8
30	−11·2	−6·6	−1·0	+ 3·3	+ 8·0	+ 6·0	+ 6·2	+ 5·5	+1·2	−4·6	− 9·7	−12·2
25	−10·5	−6·0	−0·8	+ 2·5	+ 6·2	+ 4·0	+ 4·4	+ 4·0	+1·0	−4·0	− 8·9	−11·7
20	− 9·6	−5·2	−0·5	+ 1·9	+ 4·3	+ 2·1	+ 2·4	+ 3·1	+0·7	−3·4	− 8·0	−10·4
15	− 8·6	−4·3	−0·3	+ 1·0	+ 2·9	+ 0·1	+ 0·7	+ 1·9	+0·4	−2·7	− 7·2	− 9·4
10	− 7·7	−3·2	−0·2	+ 0·5	+ 0·6	− 1·5	− 1·2	+ 0·4	+0·3	−2·0	− 6·1	− 8·1
5	− 6·1	−2·3	−0·1	− 0·5	− 1·6	− 3·5	− 3·0	− 1·0	0·0	−1·1	− 4·5	− 7·0
0	− 4·5	−1·5	−0·1	− 1·0	− 3·7	− 5·0	− 4·3	− 2·2	−0·2	−0·6	− 3·5	− 5·4

TABLE IV.—Showing how much the Mean Temperature of each Month was Higher (+) or Lower (−) than at Present for Different Latitudes.

28,300 *years ago.*

Lat. N.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Apr.-Sept.	Oct.-Mar.
°	°	°	°	°	°	°	°	°	°	°	°	°	°	°
90	0·0	0·0	0·0	−3·7	−6·3	−7·3	−7·1	−5·0	−1·2	0·0	0·0	0·0	−5·1	0·0
85	0·0	0·0	+0·3	−3·7	−6·2	−7·3	−7·0	−5·0	−0·8	0·0	0·0	0·0	−5·0	+0·1
80	0·0	0·0	+0·4	−3·3	−6·1	−7·2	−6·9	−4·9	−0·7	+0·7	0·0	0·0	−4·9	+0·2
75	0·0	+1·0	+0·4	−2·5	−6·0	−6·3	−6·1	−4·1	−0·6	+1·2	0·0	0·0	−4·3	+0·4
70	0·0	+1·6	+0·4	−2·2	−4·4	−6·1	−5·9	−3·4	−0·6	+1·2	+1·0	0·0	−3·8	+0·7
65	+1·6	+1·7	+0·4	−2·0	−3·5	−4·4	−3·9	−2·6	−0·5	+1·2	+1·7	+1·3	−2·8	+1·3
60	+2·1	+1·8	+0·4	−1·6	−3·0	−3·6	−3·2	−2·0	−0·5	+1·2	+2·0	+2·0	−2·3	+1·6
55	+2·3	+1·8	+0·4	−1·3	−2·4	−3·0	−2·8	−1·8	−0·4	+1·1	+2·1	+2·4	−2·0	+1·7
50	+2·4	+1·6	+0·3	−1·2	−2·0	−2·3	−2·2	−1·4	−0·4	+1·1	+2·0	+2·6	−1·6	+1·7
45	+2·3	+1·5	+0·3	−1·0	−1·7	−1·9	−1·9	−1·3	−0·3	+1·0	+1·9	+2·5	−1·4	+1·6
40	+2·2	+1·4	+0·2	−0·9	−1·3	−1·6	−1·6	−1·1	−0·2	+0·9	+1·8	+2·4	−1·1	+1·5
35	+2·2	+1·2	+0·2	−0·7	−1·1	−1·2	−1·3	−0·9	−0·2	+0·9	+1·7	+2·1	−1·1	+1·4
30	+2·1	+1·1	+0·2	−0·6	−0·7	−0·9	−1·0	−0·7	−0·2	+0·7	+1·6	+2·0	−0·6	+1·3
25	+1·8	+1·0	+0·2	−0·4	−0·5	−0·6	−0·7	−0·5	−0·1	+0·6	+1·4	+1·9	−0·5	+1·2
20	+1·6	+0·8	+0·1	−0·3	−0·3	−0·3	−0·4	−0·3	−0·1	+0·5	+1·2	+1·6	−0·3	+1·0
15	+1·3	+0·7	+0·1	−0·2	0·0	0·0	−0·1	−0·2	0·0	+0·4	+1·0	+1·4	0·0	+0·8
10	+1·0	+0·6	+0·1	−0·1	+0·1	+0·3	+0·2	0·0	0·0	+0·3	+0·8	+1·2	+0·1	+0·7
5	+0·9	+0·4	0·0	0·0	+0·3	+0·5	+0·4	+0·2	0·0	+0·2	+0·7	+1·0	+0·2	+0·5
0	+0·6	+0·3	0·0	+0·1	+0·5	+0·7	+0·6	+0·3	0·0	+0·1	+0·5	+0·7	+0·4	+0·4

9100 *years ago.*

Lat. N.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Apr.-Sept.	Oct.-Mar.
°	°	°	°	°	°	°	°	°	°	°	°	°	°	°
90	0·0	0·0	0.0	+2·5	+4·1	+4·4	+4·2	+3·1	+0·7	0·0	0·0	0·0	+3·2	0·0
85	0·0	0·0	−0·2	+2·2	+4·1	+4·4	+4·2	+3·1	+0·5	0·0	0·0	0·0	+3·1	0·0
80	0·0	0·0	−0·2	+2·1	+4·0	+4·4	+4·1	+3·1	+0·4	−0·3	0·0	0·0	+3·0	−0·1
75	0·0	−0·6	−0·2	+1·5	+3·9	+4·3	+4·1	+2·7	+0·4	−0·6	0·0	0·0	+2·8	−0·2
70	0·0	−0·9	−0·2	+1·3	+3·5	+3·6	+3·5	+1·9	+0·4	−0·7	−0·5	0·0	+2·4	−0·4
65	−0·9	−1·0	−0·2	+1·2	+2·7	+2·8	+2·6	+1·5	+0·3	−0·7	−1·0	−0·6	+1·9	−0·7
60	−1·2	−1·1	−0·2	+0·9	+1·9	+2·2	+2·0	+1·3	+0·3	−0·7	−1·1	−1·1	+1·4	−0·9
55	−1·3	−1·1	−0·2	+0·8	+1·7	+1·9	+1·7	+1·2	+0·3	−0·7	−1·2	−1·3	+1·3	−1·0
50	−1·4	−1·0	−0·2	+0·7	+1·5	+1·5	+1·4	+1·1	+0·2	−0·6	−1·2	−1·4	+1·1	−1·0
45	−1·5	−0·9	−0·1	+0·6	+1·3	+1·2	+1·1	+0·8	+0·2	−0·6	−1·2	−1·4	+0·9	−1·0
40	−1·4	−0·8	−0·1	+0·5	+1·2	+0·9	+0·9	+0·7	+0·2	−0·5	−1·1	−1·3	+0·7	−0·9
35	−1·2	−0·7	−0·1	+0·4	+0·9	+0·7	+0·7	+0·6	+0·1	−0·5	−1·0	−1·2	+0·6	−0·8
30	−1·1	−0·6	−0·1	+0·3	+0·8	+0·5	+0·6	+0·5	+0·1	−0·4	−1·0	−1·2	+0·5	−0·7
25	−1·0	−0·5	−0·1	+0·2	+0·6	+0·4	+0·4	+0·4	+0·1	−0·4	−0·9	−1·1	+0·4	−0·7
20	−0·9	−0·5	−0·1	+0·2	+0·4	+0·2	+0·2	+0·3	+0·1	−0·3	−0·8	−1·0	+0·2	−0·6
15	−0·8	−0·4	0·0	+0·1	+0·3	0·0	+0·1	+0·2	0·0	−0·2	−0·7	−0·9	+0·1	−0·5
10	−0·7	−0·3	0·0	0·0	+0·1	−0·1	−0·1	0·0	0·0	−0·2	−0·6	−0·7	0·0	−0·4
5	−0·6	−0·2	0·0	0·0	−0·1	−0·3	−0·3	−0·1	0·0	−0·1	−0·4	−0·6	−0·1	−0·3
0	−0·4	−0·1	0·0	−0·1	−0·3	−0·5	−0·4	−0·2	0·0	−0·1	−0·3	−0·5	−0·2	−0·2

Now, considering first the condition 28,300 years ago, we see that the summer half of the year was then cooler than now, viz. not less than 5° C. between the Pole and 80° N., and from 3½° to 2° C. in Sweden. As to the polar region, this might signify partly that the temperature was really somewhat lower, partly that a less quantity of snow and ice was melted by the summer sun at that time than at present. But as to Sweden, certainly almost the whole diminution of heat has shown itself as fall of temperature. It will be worthy of an inquiry, if there did not perhaps occur at that time a local increase of glaciation within the Kola Peninsula, Jemtland, and other countries, as has been pointed out by several geologists.[1] No doubt the fall of temperature is considerable enough to produce such an effect.

But as to the winter half of the year, it is rather uncertain if the temperature then was 1° or 2° C. higher than now, as the calculation indicates. For, as shown by the temperature charts[2] for Sweden, the January temperature of our country is about 12° C. higher than it ought to be according to the latitude, and the overplus for the whole winter half of the year will probably not be much less. But this great positive anomaly is due exclusively to the influence of the Atlantic continuation of the Gulf Stream and the warm South-westerly winds produced by it and by other causes. It might have been that the overplus of temperature on the Atlantic from 20° to 60° N. lat. 28,300 years ago so much enfeebled the Gulf Stream that the winter was not milder than now.

Further, considering the state of the temperature 9100 years ago, we see that the summer half of the year was warmer then than now, viz. between the Pole and 75° N. about 3° C., and in Sweden from 2° to 1°·3 C., which perfectly agrees with the result deduced from the above inquiry of Gunnar Andersson's on the northern limit of the hazel in Sweden at both epochs, and with the other conclusions drawn by geologists and botanists from their inquiries. As the overplus of temperature amounted to fully 2° C. in Middle Sweden and Southern Finland, and moreover the sun remained above horizon longer than now, it will be quite explicable that the water-calthrop could then ripen its fruits in the lakes of these regions.

As to the winter, we cannot here draw any conclusions. But it might be possible that this season, owing to the influence of the Atlantic continuation of the Gulf Stream, was as mild, or even milder, then as it is at present.

Still, a conclusion of great climatic and geological interest may be drawn from our curve (Fig. 4) or Table of the variation of the obliquity of the ecliptic. Indeed we have already remarked that a period with warm summers ought to have occurred 48,000 years ago. Now, as however the phyto-paleontologists of our country have not discovered more than one marked period of a richer and more southerly type than now, viz. that which occurred 9000 years ago, we must assume that 48,000 years ago the ice covering Sweden during the Great Ice Age had not yet melted away completely, or at least had so lately melted that a richer flora had had no sufficient time to establish itself. *Thus the end*

[1] Gunnar Andersson, "Den Centraljämtska issjön" ("The Ice Lake of Central Jemtland"), *Ymer*, 1897, p. 63.
[2] N. Ekholm, *Ymer*, 1899, *l.c.*

of the Great Ice Age cannot have occurred more than about 50,000 *years ago.* It may possibly have occurred later, but it seems not improbable that the exceptionally intense insolation which, according to the formula of Stockwell, must have taken place during the summer of the northern countries from 50,000 to 46,000 years ago has materially contributed to the melting away of the ice covering, and thus put an end to the Great Ice Age. The principal cause of the gradual rise of temperature about that time must, of course, be attributed to a slow increase of the quantity of carbonic acid in the air, as shown in the two foregoing chapters.

The periodic climatic variation here discussed cannot, as far as I can judge, have caused any sensible variation of the rain. The rather damp and rainy period with mild winters which, according to the opinion of most geologists, has occasioned the immigration of the Ilex flora to the west coast of Scandinavia cannot therefore be explained thereby. Possibly such a variation of climate was caused exclusively by geographical causes, as, during the land depression called by Swedish geologists the Litorina depression, the lukewarm water of the North Sea had a more open access to the coasts of the Scandinavian Peninsula than it has now.

According to the opinion of some Scandinavian botanists, particularly Axel Blytt and Rutger Sernander, the Scandinavian Peninsula has had several alternating periods of dry and damp climates during the Quaternary Age, which have given rise to alternating growths of wood and moss, indicated by alternating layers of tree-stools and moss in the Scandinavian swamps. As it seems to me at present impossible either to contest or to confirm this opinion by means of physical investigation, it may be left to future research, so much the more as the question is still much in dispute among botanists and geologists.

After writing the above, I have found that this point has already been considered by J. Croll,[1] who, by a method of calculation different from that which I used, obtained a result as to the temperature of the poles during the summer that does not differ noticeably from that given in this paper. According to Croll:[2] "When the obliquity of the ecliptic was at a maximum, and the poles were receiving $\frac{1}{18}$th more heat than at present, the temperature of the poles ought to have been about 14 or 15° Fahr. warmer than at the present day, provided, of course, that this extra heat was wholly employed in raising the temperature. Were the polar regions free from snow and ice, the greater portion of the extra heat would go to raise the temperature. But as these regions are covered with snow and ice, the extra heat would have no effect in raising the temperature, but would simply melt the snow and ice. The ice-covered surface upon which the rays fell could never rise above 32°. At the period under consideration the total annual quantity of ice melted at the poles would be $\frac{1}{18}$th more than at present." So far Croll. If we suppose, in agreement with the statement made by Croll on p. 400, that the rise of 14° or 15° Fahr. is meant to take place under the above condition only during the middle of summer, then Croll's result agrees very closely with that given here. But supposing that

[1] J. Croll, *Climate and Time*, London, 1875, p. 398 *et seq.*
[2] J. Croll, *l.c.* p. 402.

the yearly average were considered, a rise of 14° or 15° Fahr. would be about three times too much. Also the remarks of Croll as to the influence of this variation on the temperature in other latitudes are essentially correct. But as the biological and geological facts, which in this paper are explained as a consequence of the variations of the obliquity of the ecliptic, were still very little known in 1875, Croll did not develop his theory on this matter more in detail. And as the variation of the eccentricity of the earth's orbit is, according to him, the principal cause of the great changes of climate during the geological past, his chapter on the obliquity of the ecliptic seems not to have been duly estimated. I wish now to acknowledge Croll's indisputable priority as to the theory in question.

7. *Climatic variations during historical times, particularly in North-Western Europe.*

It remains to consider the variations of the climate during the historical period. Here we certainly find a richer material of observations than before, but at the same time such a want of order and regularity that it seems at present nearly impossible to obtain a survey of and establish a connection between the shifting phenomena. Here we cannot see the wood for trees. First, during the last hundred or hundred and fifty years, since there began to be regular meteorological observations, the survey becomes easier; but then, on the other hand, the time is too short, so that from this reason no reliable conclusions can be drawn. Moreover, the material is so rich that the energy of a single man is insufficient to work it out. I must then confine myself to a short sketch of the climate of Scandinavia and the adjacent countries.

Almost the only weather phenomenon of which the old chronicles give trustworthy reports are severe winters. The following statements thereof are partly taken from Ehrenheim,[1] partly collected by Prof. R. Rubenson and by him kindly placed at my disposal. The year of the winter is determined by January, yet it is sometimes doubtful whether the chronicler has not taken it from December. Sometimes the winter is indicated by the numbers of both years separated by a break. Possibly in some case a severe winter has thereby been doubled.

The Skager Rack and the Catte Gat (Ehrenheim writes, "the North Sea between Norway and Denmark") were frozen and available for traffic for men and animals in the winters 1048, 1224-25, 1294 and 1296(?) [people rode from Oslo (Christiania) to Jutland], 1394, 1399, 1407-8, 1423-24.

The south part of the Baltic was covered with ice which would bear traffic in the winters 1294, 1306 (people travelled over the ice between Öland, Gotland, and Esthonia), 1322-23 (people walked and rode between Denmark and Germany, and between Scania and Sealand, and had regular lodgings on the ice), 1324 (the Baltic was frozen during six weeks), 1393-94 and 1399 (people walked between Denmark and Pomerania), 1407-8 and 1418 (people walked on the ice between Germany and Denmark), 1423-24 (people rode on the ice from Danzig to Lubeck, and had lodgings on the ice), 1426 (similar winter), 1458-59

[1] Ehrenheim, "The Variability of the Climates," cited above.

and 1459-60 (the whole Baltic was covered with ice, so that people went on foot and on horseback from Germany to Sweden and Denmark, likewise from Livonia, and this still at the end of March), 1545 and 1546 (?) (the Baltic frozen between Mecklenburg and Denmark), 1573 (on the Thursday before Whitsuntide people came on the ice from Sweden to Reval), 1636 (people walked on the ice from Scania to Bornholm till March 21), 1658 (the Swedish army went over the Little Belt), 1670 (the Little and Great Belts frozen), 1708-9 (the Belts and the Sound covered with ice, people travelled on the ice from Gothenburg to Marstrand, and still in June ice was left between the cliffs along the shore of the Baltic east from Stockholm. The Baltic was covered with ice as far as could be seen by means of telescope from the church steeple of Danzig. The port of Genoa was partly frozen, the Adriatic covered with ice, which had not happened since 859), 1776 (the Sound and the Belts frozen, likewise the Zuider See, but not the Sea of Åland, N.W. from Stockholm).

Also from middle and south of Europe both Ehrenheim and foreign meteorologists report accounts taken from the old chronicles about winters so severe that they far surpass those of our time. According to Ehrenheim, these winters began to occur about 300 years before Christ, and then have been comparatively frequent during the first thousand years of our era. In the year 250 the Thames was frozen for nine weeks; 508 English ships were imprisoned by the ice for two months. The Black Sea was frozen several times, 401 (in twenty days), 673 (ice several ells thick), 800-801 (ice several feet thick). In 763 all the Black Sea, and even the Dardanelles, were filled with ice; in the same winter the snow in many places lay 50 feet deep. The Adriatic was covered, 859-60, with ice which bore traffic. In 717 all Asia Minor was covered with snow during three months. In 1216 the Po was covered with ice, likewise in 1234 when the ice around Venice supported heavy waggon loads. From November 1334 to March 1335 a severe cold reigned in all Europe; all rivers in Italy were frozen. In 1608 the Bosphorus was covered with ice, in 1621 likewise, and moreover the Gulf of Venice.

"One might conclude," says Ehrenheim, "that the extremes of cold have decreased from the following facts:—since 1424 there is no instance that the Skager Rack has been frozen, since 1573 none that people have gone on the ice from Livonia to Sweden and Denmark, since 1621 none that the Bosphorus has been covered with ice, since 1635 (1636 ?) none that the Baltic has borne traffic between Scania and Bornholm, since 1709 none that ice has been prevalent in the Adriatic."

On the other side, according to Ehrenheim, the summers of Western Europe have become cooler. "In Normandy the vine in older times was cultivated with great success, and it was in the Middle Ages that the vineyards north from the Cevennes were celebrated. In the fourteenth century people were at last obliged to abandon this culture, and instead of it to plant apple trees in order to make cider. The Paris wines were formerly served at kings' tables. In Languedoc there were, until 1561, great vineyards on the slope of the mountain range that divides the province; there now grapes cannot even redden. In England also the vine had been cultivated during all the Middle Ages ever since the time of the Romans, and there exist old household accounts of hogsheads of wine produced in the vineyards of Northampton and Leicester." Thus "we find here again the contrast that the vine produced ripe grapes in England and Normandy at a time when the Skager Rack froze, but has not been able to do the same afterwards when this winter cold had ceased."

The first conclusion of Ehrenheim, viz. that the extremes of winter cold have decreased, seems indisputable if we compare the state of the ice in the Scandinavian waters formerly and now. Nowadays (during the nineteenth century, more detailed reports since 1870) this is as follows. On the west and south coast of Sweden the navigation is only during severe winters somewhat hindered by ice, mostly by drifting ice. Compact sea ice within sight from the outermost lighthouses, as Vinga and Väderöbod, is rare, continues ordinarily only for a few days, and in extremely rare cases will bear a man, as for instance in February and March 1888. About the same are the ice conditions on the Skager Rack along the south-east coast of Norway. At the end of February 1893, however, the sea was covered with ice along the whole coast from Christiansand (Oxö) to Christiania, as far as the eye could see. During very severe winters the Sound has been covered with ice which would bear waggons. The northern and middle portions of the Baltic, from the Sea of Åland to the south end of Gotland, Öland and Calmar Län (government), outside the cliffs along the shore, are covered with ice only during very severe winters, and then ordinarily only for a few days or even weeks, and only for ten or twenty kilometres from the coast. Drifting ice is more common, and during very severe winters may be piled up in gigantic masses of crowded ice. Thus on February 25, 1893, they reported from Sandhamn (59° 17′ N., 18° 56′ E. fr. Gr., a port east of Stockholm): "The solid ice is lying 1½ mile outwards; . . . farther outside the sea is filled up by very heavy drifting ice, high as the rigging of the largest ship." It is only during very mild winters that the navigation can go on quite without hindrance; between Stockholm and Visby it ceases, on an average, in the end of December and begins again about April 10. During very severe winters the Sea of Åland is covered with ice which bears traffic. The Botten Sea (= south part of the Gulf of Bothnia) is covered with ice every winter along the coasts, but rarely, if ever, in its central part. The navigation there is interrupted, by compact or drifting ice, on an average from the middle of November to the beginning of May, with some difference for different ports and up to a variation of six to eight weeks for different years. Sometimes it has happened that the port of Hernösand has been free from ice during a whole winter. The northern Quarken (the strait between the southern and northern parts of the Gulf of Bothnia) has been covered with ice which bore traffic about every third or fourth year since 1816, namely in the years (date = that of January) 1816, 1830, 1831, 1839, 1844, 1845, 1853, 1855, 1856, 1857, 1861, 1862, 1865, 1866, 1867, 1875, 1876, 1877, 1879, 1881, 1886, 1888, 1893, 1895, and 1897 (is said to have been strong enough this year, though the traffic was not undertaken). The Botten Gulf (= north part of the Gulf of Bothnia) is as a rule frozen every winter. The ice formation occurs along the coast on an average about the middle of November, sometimes at the end of October or the beginning of December. The breaking up arrives on an average during the later half of May, extremely rarely in the beginning of that month, sometimes not until the beginning of June.

Thus, although a considerable formation of ice on the Scandinavian seas occurs also at the present time during severe winters, nevertheless it is evident that the ice-covering on the Baltic, the Sound, the Belts, the Catte Gat, and the Skager Rack was very much more extensive during the Middle Ages, particularly from the eleventh to the fifteenth centuries, than afterwards.[1] It is difficult for us to understand what the weather might be during a winter which covers with thick ice all the southern part of the Baltic, the Catte Gat, and the Skager Rack. Such a winter must have had not only a severe and continual cold, but also relatively calm weather, otherwise the ice would have been broken up into drifting or crowded ice-flakes, and hence not have been suited for traffic. In the above-cited paper[2] I have made a study of the severe winters in Sweden from about 1870. Such a winter begins in our time with snow-storms generated by cyclones situated south or south-east from our peninsula, *i.e.* in the southern or south-eastern part of the Baltic. Then gradually an anticyclone extends over the Norwegian Sea. Now if we imagine that these cyclones, after the whole country had been covered with snow, were pushed off always farther to the south-east as far as to the Black Sea and Asia Minor, whereas the anticyclone extended from the icy ocean and the Norwegian Sea over all Scandinavia and Finland, Western and Central Europe, and Northern Russia, and that such a state of barometric pressure was accompanied by a sky generally clear and light winds, so that a strong radiation continued during two or three months, then we might have an idea about the probable state of weather during the winters 1322-23, 1423-24, or 1459-60.

But such winter weather, as far as we know, has not occurred in our time; for the cold winters in our days are always characterised by frequent cyclones, which from time to time are passing over Sweden or not far to the south of it. Ordinarily they come from the west, and no doubt are generated or maintained by the Atlantic continuation of the Gulf Stream. It would therefore seem to be the explanation nearest at hand that the Gulf Stream was feebler or had another and more westerly direction during the Middle Ages than now, and by consequence the climate of that time was more continental than it is now. In the latter case the climate of Iceland and Greenland would have been milder than at present. I do not know, however, any plausible cause for such a variation in the direction of the Gulf Stream.

But that Iceland and Greenland at the time of their colonising by the old Scandinavians (Northmen) and afterwards during the succeeding centuries really had a somewhat milder climate than the present one seems to come out from the old sagas and chronicles of the Middle Ages, as, for instance, Ehrenheim and A. E. Nordenskiöld have pointed out. "It is now disputed," says Ehrenheim in 1824, "that the east coast of Greenland was ever inhabited and cultivated; it is indifferent when we

[1] What the conditions in our waters were before the eleventh century is unknown, as the old sagas do not tell us about it.

[2] *Ymer*, 1899, p. 221 *et seq.*

compare the whole land formerly and now. It was discovered more than 900 years ago, and history testifies that there existed woods and pasture lands inviting colonists, and that it was so successfully cultivated in agriculture and breeding of cattle that after 200 years there were to be found 196 hamlets,[1] 12 churches, several monasteries,[2] and a bishop's see. In this condition the land disappears from history in the middle of the fourteenth century, when the communications with Iceland were interrupted. During the seventeenth century Lindenau, Hudson, and many others made fruitless efforts to find this land again, and when at length it was again discovered and examined on its west coast all culture was found to have been effaced by the severity of the climate, and the wild inhabitants told Crantz that straits and inlets formerly had been navigable which now were covered with ice. This variation in the climate seems to have continued during all the eighteenth century, to judge from the decrease of the population; for where the Bishop Egede in 1723 found about 30,000 inhabitants on all the west coast, there Giesecke in 1813 found only 6583. The younger Egede, in his journal of 1770-78, tells us positively that the icebergs in Greenland are increasing yearly. Iceland, which was still more flourishing in its prosperity, has undergone a similar fate. There the woods have become extinct, the agriculture has disappeared, the population diminished by more than a half. It seemed to Von Troil that this island approached the fate of Greenland."

Ehrenheim's description of the change of the climate in Greenland might be exaggerated, but that some change in the indicated direction has occurred results from the inquiries made by the Danes during the last twenty years. G. F. Holm,[3] then first lieutenant of the Danish navy, in the years 1880 and 1881 examined the southernmost part of Greenland (the district of Julianehaab), from 61° 15′ N. and 46° 20′ W. to 60° 15′ N. and 43° 0′ W. fr. Gr., and found there a great many old ruins from the Northmen's colonies, situated mostly at the heads of the fjords between 46° 14′ and 43° 58′ W. This region has formerly been partly examined and described, especially in the great Danish work *Grönlands historiske Mindesmærker* ("The Historical Monuments of Greenland"). This is no doubt the old "Österbygden" (the chief colony), for the number of ruins found agrees very nearly with the old relations of the chroniclers.[4] Holm says (*l.c.* p. 72): "In summer there was in the neighbourhood of all the greater groups of ruins a rich store of fodder for great flocks of cows and sheep, but in what manner they in those times could find sufficient winter fodder for the cattle is difficult to understand, unless we assume that the climate formerly was milder, so that it was possible for the cattle to stay out of doors a longer time of the year than now is the case. That the ice-drift along the coast has increased in historical times is stated by the old chroniclers, and seems to be a necessary condition in order to understand how the old Northmen were able to navigate in the present district of Juliane-

[1] 190 hamlets, according to the newer statements. See farther on.

[2] Two monasteries, according to newer statements.

[3] G. F. Holm, "Description of Ruins in the District of Julianehaab" (Danish), *Meddelelser om Grönland*, 6 Heft, Kjöbenhavn, 1883, pp. 57 and 147.

[4] See further Daniel Bruun, "Archæological Inquiries in the District of Julianehaab" (Danish), *Meddelelser om Grönland*, 16 Heft, 1896, p. 171 and following.

haab; and, moreover, it cannot be denied that this ice, which now is lying everywhere outside this part of the land, considerably increases the severity of the weather." Further, he speaks (p. 74) about enclosures "situated outside the house on a fertile soil on southern slopes in the vicinity of running water," and which "perhaps have surrounded gardens"; hand-mills (p. 75) of which is said: "If the corn, as told in the old chronicles, has been cultivated there, the climate, as said above, must then have been milder than now; more probably, however, the corn has been brought to them by means of the ships." The principal business of the people was breeding of cattle (horses, cows, sheep, and goats), fishing and hunting; but, says Holm (p. 75), "that the principal trade of the Northmen has not been confined to the sea, follows from the circumstance that so many greater groups of ruins are situated in a considerable distance from the fjords." After the middle of the thirteenth century the colony began to come to ruin (*l.c.* p. 61). "The sea ice at the eastern coast of the land increased in a degree hitherto unknown; as a consequence of it shipwrecks seem to have become frequent." In the next century the navigation was moreover impeded by an injurious trade monopoly introduced by the Norwegian kings, and the Skrælings (Esquimaux) attacked the colonists. First they destroyed the north-western (now Godthaab) district (the old Vesterbygden); at last, probably at the end of the fifteenth century, also the south-eastern (now Julianehaab) district (the old Österbygden).[1] Afterwards, when the land was discovered again, the Norwegian population had disappeared. Modern Greenland (Esquimau) tales speak of struggles in which the last "Kablunaks" (Norwegians) were extirpated.[2] Holm, however, believes that the last inhabitants of the forgotten colony have gradually turned to the manner of living of the Esquimaux and mixed with them, by which the East Greenlanders have assumed a half-Norwegian type. Thus it has not been exclusively the deterioration of the climate in Greenland which has spoiled the old colony, though this may have been a contributing cause. According to Finnur Jónsson, the corn culture was very slight, or did not succeed, at least in the beginning, for not even the first chief of the land, Erik Röde (Erik the Red), had barley for his Yule ale. Daniel Bruun[3] tells us that the present Greenlanders (Esquimaux) in these regions successfully practise breeding of cattle. The cows go, as a rule, out of doors from April or May to October, and during the winter are foddered with hay which the inhabitants make along the coasts and bring home in their umiaks (women's boats). At Igaliko they have begun in the last years to plant turnips as fodder for the cattle.

As to the second statement of Ehrenheim, viz. that the summers in Western Europe during the Middle Ages were warmer than now, it is more doubtful than the former. That the vine is no longer cultivated as far to the north as formerly, several writers are inclined to explain by the assumption that people were formerly content with a worse and more acid wine than now, made even from rather unripe grapes.[4]

[1] Thus it seems as if the Esquimaux have wandered to the south, which may be considered as still a proof that the climate in Greenland has deteriorated.

[2] Finnur Jónsson, "A Brief Sketch of the History of the Greenland Colony" (Danish), *Nordisk Tidskrift*, Stockholm, 1893, p. 533.

[3] Daniel Bruun, *l.c.* p. 252 and following, p. 322 and following.

[4] Alfred Angot ("Études sur les vendanges en France," *Annales du Bureau Central*

I shall now give some observations which likewise seem to prove that the winters have become milder in the Scandinavian countries during the last three hundred years, and that at least during the last century the summers in Great Britain, Denmark, and South Sweden have been somewhat cooler—in short, that the climate has grown more maritime.

The most important of these observations are those which Tycho Brahe carried out during the period October 1582 to April 1584, and August 1584 to April 1597 inclusive (= 14 years 4 months), at his observatory, Uranienborg (55° 54′ N., 12° 43′ E. fr. Gr.), in the little island Hven in the Sound, and which have been calculated by Poul la Cour and published *in extenso* by the Royal Danish Society of Sciences.[1]

Poul la Cour finds several differences between the climate of Hven 300 years ago and the present climate in adjacent districts of Denmark—differences the signification of which, however, he seems to underrate. He remarks that the number of snow days in February is much greater according to Tycho Brahe than according to present observations, and that at the same time the number of rain days in this month is very small according to the old series, which agrees with what results from several circumstances, namely, that the month of February has been cold and severe throughout. Further, Poul la Cour finds a considerable difference in the wind directions then and now—so great, indeed, that it seems impossible to attribute it to errors of observations or to accidents. Whereas in our time South-west is the prevailing wind direction on the yearly average, and South-west or West during all months except April or May, when South-east is somewhat more frequent, in Tycho Brahe's time South-east was decidedly prevalent in the yearly average, and East or South-east during seven of the months of the year, viz. January to May inclusive, October and December, and even during the other five months the South-east wind shows a secondary maximum, of which now scarcely a trace is seen. From this we must conclude that the distribution of atmospheric pressure during the winter was then essentially different from the present one; the low pressure which in our time is to be found regularly between Norway and Greenland and in the northern ice ocean was then necessarily but little marked. Owing to this low

météorologique de France, 1883, i., Paris, 1885) has examined whether the mean date of the vine harvest in France has undergone any secular change, but has not found any progressive one, and hence concludes that the state of the vine culture does not indicate any deterioration of the summer climate there. He remarks, however, that the date of the vine harvest depends also on other circumstances than the climate. But that the mean date of the vine harvest really has been a little retarded during the last 500 years seems to follow from the averages of Dijon, which are in the fourteenth century October 25 (mean of only 13 years); in the fifteenth century, October 25 (mean of 60 years); in the sixteenth century, October 28; in the seventeenth century, October 25; in the eighteenth century, October 29; and in the nineteenth century October 30 (mean of 80 years), and from hence we might possibly conclude some secular decrease of the summer heat at Dijon. Whether the vine formerly was cultivated in regions where it does not thrive now, Angot does not tell us.

[1] Tyge Brahe's *Meteorologiske Dagbog, holdt paa Uraniborg for Aarene, 1582-1597. Udgiven som Appendix til Collectanea Meteorologica af det Kgl. Danske Videnskabernes Selskab ved dets meteorologiske Comité*, Kjöbenhavn, 1876. With a supplement: "Summary of the Weather Observations in the Meteorological Journal of Tycho Brahe," by Poul la Cour (Danish and French). During the three months May, June, and July 1584, the observer made a voyage to Frauenburg in Prussia, during which observations were also carried on. This remarkable journal contains probably one of the oldest series of meteorological observations existing.

pressure the cyclones at present are passing usually from west to east over the northern or middle part of the Scandinavian Peninsula, producing South-west winds in the Sound. But the East or South-east winds which in Tycho Brahe's time reigned during the winter prove that the cyclones then took a more southerly track, and as a rule were passing west and then south of Hven, for instance from the North Sea through the southern part of Denmark to Germany, a track at present taken by the cyclones almost exclusively during the spring months of ordinary years and during unusually severe winters. Also the North-east winds were then generally more frequent than they are now. Likewise the examination of the frequency of storms shows a difference, the number of storms in February and March being in Tycho Brahe's time less than the yearly average, whereas the case now is inverse. Moreover, the number of East and South-east storms was then relatively greater than now, as one might expect according to the different wind roses. All these differences between the climate of that time and the present one agree with what was said above of the probable distribution of pressure and weather during the severe winters of the Middle Ages.

We possess now a very complete series of observations on the temperature, rainfall, and weather at Uranienborg for the years 1881-98 inclusive, carried out by the farmer J. J. Alm, under the instruction of the Meteorological Central Office in Stockholm and by means of its instruments. Thus we are able to make a direct comparison between the climate of Uranienborg at Tycho Brahe's time and at present, although, of course, the want of meteorological instruments causes difficulties in the case of the old series.

Firstly, I have calculated the mean date of the last spring frost and the first autumn frost. The word *frost* is not to be found all years in the old series. In these cases I have used such expressions as "ice on the water in the morning," "great snow," "hail and snow," "cold snow," etc. By adding ten days to the date of Tycho Brahe it was reduced to the new style. In the new series I have counted as frost days those when the minimum temperature was below 0° C. In this manner I derived the following result:—

Year.	Last spring frost.	First autumn frost.
1582-1597 . . .	April 18	October 27
1881-1898 . . .	,, 19	,, 28

Hence it seems to follow that the conditions of temperature during the spring and the autumn have not varied.

From the observations of Tycho Brahe, Poul la Cour has calculated the probability of a day of precipitation, rain, snow, hail, thunder for every month of the new style. I have calculated corresponding values from the new observations and put the results together in the following Table. The signification of the numbers of the Table is thus: for instance, the probability of a day of precipitation in June 1582 to 1597 being 0·360, this indicates that precipitation (*i.e.* rain, snow, hail, etc.) fell on an average in 360 days of 1000.

First, it may be remarked that the numbers of the two series are not perhaps quite comparable, for probably the annotations from Tycho Brahe's time are not so exact as those of the new series, as an inspection of the two series seems to indicate. Accordingly, the numbers of the new series are generally somewhat greater. From this rule there are, however, two remarkable exceptions. The month of June had in the old series a greater number of days with precipitation, rain, hail, and thunder, whereas the figures for the months July, August, September, and October were less than the present values (with only some unimportant exceptions as to hail). This indicates that the summer

TABLE V.

Year.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.
					Probability of a day of precipitation.							
1582-97	0·290	0·250	0·310	0·250	0·210	0·360	0·370*	0·380*	0·330	0·340	0·350	0·340
1881-98	0·337	0·291	0·362	0·269	0·315	0·316	0·406	0·467	0·349	0·446	0·390	0·362
					Probability of a day of rain (without snow or hail).							
1582-97	0·181	0·086	0·123	0·204	0·207	0·359	0·377	0·381	0·330	0·339	0·310	0·233
1881-98	0·172	0·135	0·193	0·214	0·298	0·312	0·402	0·463	0·343	0·420	0·325	0·227
					Probability of a day of snow (with or without rain or hail).							
1582-97	0·129	0·188	0·194	0·053	0·008	0·000	0·000	0·000	0·000	0·009	0·048	0·129
1881-98	0·163	0·154	0·167	0·051	0·002	0·000	0·000	0·000	0·002	0·009	0·061	0·135
					Probability of a day of hail (with or without rain or snow).							
1582-97	0·007	0·010	0·014	0·015	0·011	0·015	0·005	0·005	0·015	0·007	0·017	0·015
1881-98	0·002	0·002	0·002	0·004	0·015	0·004	0·004	0·004	0·004	0·017	0·004	0·000
					Probability of a day of thunder.							
1582-97	0·000	0·003	0·000	0·003	0·028	0·053	0·043	0·034	0·015	0·000	0·000	0·000
1881-98	0·000	0·000	0·000	0·012	0·045	0·049	0·097	0·076	0·027	0·015	0·002	0·000

* Here there is some little error in Poul la Cour's calculation, as these numbers cannot be less than what corresponds to days of rain.

climate was then more continental than now. For in Scandinavia and adjacent countries the more continental climate is characterised by prevailing rain and thunder in the middle of the summer; the more maritime one, on the contrary, by prevailing rain and thunder in the latter part of the summer and autumn.

Still more striking is the difference in the number of snow days during February and March. In order to show this quite obviously I give here—

The Number of Snowy Days as a Percentage of the Number of Days of Precipitation at Uranienborg.

Year.	Oct.	Nov.	Dec.	Jan.	Feb.	March.	April.
1582-1597 . .	3	14	38	45	75	63	21
1881-1898 . .	2	16	37	48	53	46	19
Difference . .	+1	−2	+1	−3	+22	+17	+2

As a greater percentage of snow days signifies a lower temperature, we see that February and March were decidedly colder 300 years ago than now, whereas the difference for the other months is nearly evanescent. By combining the number of snow days, expressed as percentages of the number of days of precipitation, for every month of the new series with the corresponding mean monthly temperature I have tried to calculate the difference between the mean temperature in Tycho Brahe's time and the present one,[1] and hence, knowing the latter, have determined the former. The result is this :—

Mean Temperature of the Winter Half of the Year at Uranienborg.

Year.	Nov.	Dec.	Jan.	Feb.	March.	April.
1582-1597	+3°·9	+0°·8	−0°·9	−2°·3	−0°·3	+5°·0
1881-1898	+3·7	+0·9	−1·1	−0·9	+0·7	+5·2
Difference	+0·2	−0·1	+0·2	−1·4	−1·0	−0·2

Thus 300 years ago February was 1°·4 C. colder than now, and March 1° C., whereas the difference for the other months amounts only to 0°·2 in the one or other direction.

Also the observations of the ice-covering in the Sound seem to indicate that the winters 300 years ago were more severe than now. For, according to the old series, a coating of solid ice occurred on an average in 10 out of 15 winters (1582-97) during about 17 days per winter, whereas in our time during the 29 winters 1870-99 it occurred during 15 winters, with an average of 16 days per winter. Drifting ice alone was observed during these 29 winters in 2 winters, with an average of 8½ days per winter, but this does not seem to have been regularly noted in the old series. Probably the difference would have been greater if the old observations had been as exact as the new ones. The latter consist of the reports from the pilot stations on the Sound, especially from Landskrona (55° 52′ N., 12° 50′ E. fr. Gr.), not far from Hven. These reports are sent every year to the Royal Swedish Direction for the Pilot Service. From the island Hven itself, as far as I know, there are no observations on the ice-covering made in our time.

As known, Brückner[2] has tried to show, in a great treatise, that the climate is subject to periodical variations of warmer and colder intervals, with a length of period amounting on an average to 34·8 years. These variations he considers to be simultaneous for the whole earth. The cause of this climatic variation is, according to Brückner, quite unknown, and the phenomenon itself, if we judge from the material worked out by him, very irregular. It is, however, interesting to examine if the difference between the climate of Hven in 1582-97 and 1881-98, as shown above, is connected with Brückner's period. Now, according to him,[3] the weather was warm, 1581-90; cold, 1591-1600; cold, 1876-90; warm, from 1891 (inclusive). We see that out of Tycho Brahe's series, according to Brückner, 8 years are warm, and 6 years 4 months cold, but out of the new series 10 years are cold and 8 years warm. In consequence, the old series ought to be warmer and the new one colder than the corresponding mean value of Brückner's period, from which would follow that the climatic variation above calculated would be still somewhat greater than the observations indicate.

Finally, we shall examine what conclusions can be drawn from the

[1] In this manner I obtained for every one of the above months a Table, showing the percentage of snow days corresponding to several values of average monthly temperature. From this Table, entering in it with the percentages in the above Table as arguments, the difference of temperature sought was obtained by means of interpolation between the temperatures corresponding to the percentages of snow days. For October no reliable result could be deduced, owing to the small number of snow days in this month.

[2] E. Brückner, *Klimaschwankungen Seit* 1700 *nebst Bemerkungen über die Klimaschwankungen der Diluvialzeit*, Wien und Olmütz, 1890.

[3] E. Brückner, *l.c.* p. 271.

regular observations of the temperature made during the last 100 to 150 years.

As to Copenhagen, Willaume-Jantzen[1] has found that during the last 110 years the winters have gradually become somewhat milder and the summers somewhat cooler, and thus a variation from a more continental to a more maritime climate, in agreement with what we have found for the last 300 years from the observations of Hven. Somewhat similar results are also to be found for Scotland, according to Buchan.[2]

TABLE VI.—MONTHLY MEANS OF THE AIR TEMPERATURE.

Months.	HAPARANDA with Environs, 65° 50′ N., 24° 9′ E. fr. Gr.			STOCKHOLM OBSERVATORY, 59° 21′ N., 18° 4′ E. fr. Gr.			LUND OBSERVATORY, 55° 42′ N., 13° 12′ E. fr. Gr.			
	1802-1848 46 Years (1824 wanting).	1849-1898 50 Years.	1802-1898 96 Years.	1799-1848 50 Years.	1849-1898 50 Years.	1799-1898 100 Years.	1753-1798 46 Years.	1799-1848 50 Years.	1849-1898 50 Years.	1753-1898 146 Years.
January	−12·8°	−11·7°	−12·3°	−4·3°	−3·2°	−3·7°	−2·0°	−2·2°	−1·0°	−1·8°
February	−11·9	−11·8	−11·8	−4·4	−3·6	−4·0	−1·0	−2·0	−1·0	−1·4
March	−9·1	−8·5	−8·8	−1·7	−1·8	−1·8	0·2	0·2	0·6	0·3
April	−2·7	−2·0	−2·3	2·9	3·1	3·0	4·9	4·9	5·0	4·9
May	3·5	4·0	3·8	8·7	8·7	8·7	10·3	10·7	10·3	10·4
June	11·4	11·8	11·6	13·9	14·3	14·1	14·8	14·9	14·9	14·9
July	14·4	15·0	14·7	16·8	16·9	16·8	16·9	16·9	16·5	16·8
August	13·1	12·7	12·9	16·0	15·6	15·8	16·5	16·1	15·8	16·1
September	7·1	7·5	7·3	11·7	11·6	11·7	12·5	12·5	12·4	12·5
October	1·6	1·2	1·4	6·6	6·2	6·4	7·6	7·7	7·7	7·7
November	−5·7	−5·4	−5·5	1·4	1·3	1·3	2·9	3·2	2·9	3·0
December	−9·2	−9·9	−9·6	−2·0	−1·9	−1·9	−0·1	0·0	0·3	0·1
Winter	−11·3	−11·1	−11·2	−3·6	−2·9	−3·2	−1·0	−1·4	−0·6	−1·0
Spring	−2·8	−2·2	−2·4	3·3	3·3	3·3	5·1	5·3	5·3	5·2
Summer	13·0	13·2	13·1	15·6	15·6	15·6	16·1	16·0	15·7	15·9
Autumn	1·0	1·1	1·1	6·6	6·4	6·5	7·7	7·8	7·7	7·7
Year	0·0	0·2	0·1	5·5	5·6	5·5	7·0	6·9	7·0	7·0

We shall now see what some of the longer Swedish series of observations indicate. They have not been completely worked out, but for Lund, Stockholm, and Haparanda I have been able, however, to calculate longer series of monthly means of the temperature. All these means I have reduced, as exactly as possible, to true daily means. The Haparanda series, being a combination of three series made at different places situated in that district of Sweden, and, partly by means of a series from Torneå, reduced to the same place, viz. Haparanda, for this and other reasons is less reliable than the two others. As to Lund, my

[1] V. Willaume-Jantzen, *Meteorologiske Observationer; Kjöbenhavn. Udgivet af det Danske Met. Institut*, Kjöbenhavn, 1896, p. 17 and following (Danish and French).

[2] A. Buchan, "The Mean Atmospheric Pressure and Temperature of the British Islands," *Journal of the Scottish Met. Soc.*, 3 ser., xiii. and xiv., 1895-96, Edinburgh and London, p. 13 and following.

mean values are calculated from the five daily means published by A. V. Tidblom,[1] and completed by the Copenhagen observations. For the sake of comparison, I give also longer series from London[2] and Paris.[3] The English and the French monthly means of the temperature are means of the daily maxima and minima.

Months.	London, City with Environs, Royal Observatory, Greenwich.				Paris, City, Montsouris, Parc de Saint Maur.		
	1763-1798 36 Years.	1799-1848 50 Years.	1849-1898 50 Years.	1763-1898 136 Years.	1806-1848 43 Years.	1849-1898 50 Years.	1806-1898 93 Years.
	°	°	°	°	°	°	°
January	3·3	2·6	3·5	3·1	1·9	2·7	2·3
February	4·7	4·1	4·4	4·3	4·3	4·0	4·1
March	5·7	5·7	5·7	5·7	6·5	6·6	6·6
April	9·1	8·6	8·9	8·8	9·9	10·5	10·2
May	12·8	12·8	12·0	12·6	14·4	13·6	14·0
June	16·2	15·5	15·7	15·8	17·1	17·2	17·2
July	17·9	17·3	17·6	17·5	18·8	18·9	18·9
August	17·9	17·1	17·2	17·3	18·5	18·5	18·5
September	15·3	14·4	14·6	14·7	15·7	15·7	15·7
October	11·2	10·5	10·2	10·6	11·3	10·9	11·1
November	6·9	6·4	6·2	6·4	6·8	6·4	6·6
December	4·7	4·1	4·2	4·2	3·7	3·3	3·7
Winter	4·2	3·6	4·0	3·9	3·3	3·3	3·4
Spring	9·2	9·0	8·9	9·0	10·3	10·2	10·3
Summer	17·3	16·6	16·8	16·9	18·1	18·2	18·2
Autumn	11·1	10·4	10·3	10·6	11·3	11·0	11·1
Year	10·5	9·9	10·0	10·1	10·7	10·7	10·7

It results from this Table that the temperature of January at all three Swedish places has risen about 1° C.; but that of August has decreased somewhat, especially at Lund, where the fall amounts to 0°·7; also July has become 0°·4 cooler there in the last 50 years. Hence the climate has varied, at least at Lund, in the manner indicated above. At Lund the four months April, June, September, and October have maintained their temperature exactly constant during the three intervals, and May and November very nearly; so that it seems legitimate to state that the spring, the beginning of summer, and the autumn have not undergone any change, which agrees with what was found for the temperature in Hven during the last 300 years. As to Stockholm, it seems that none of the ten months March to December has sensibly altered its mean temperature during the last 50 years. The numbers

[1] A. V. Tidblom, "Einige Resultate aus den met. Beob. angestellt auf der Sternwarte zu Lund in den Jahren 1741-1870," *Lunds Universitets Årsskrift*, t. xii., Lund, 1876.

[2] The years 1763-1892 according to A. Buchan, "The Temperature of London for 130 years, from 1763 to 1892," *Journal of the Scottish Met. Soc.*, 3 ser., ix., 1891; and the years 1893-98 directly from the publication of the Meteorological Office in London.

[3] The years 1806-96 according to the *Annuaire de l'Observatoire de Paris, dit Observatoire de Montsouris*; the years 1897 and 1898 from Parc de Saint Maur.

for Haparanda are, for several reasons, less reliable than those for the two other places, so that one can scarcely draw from them any other conclusion than this, that the months January to July have perhaps become a little warmer. The first half of our century was characterised by many very cold winters at all the three places in Sweden; also in London and Paris, January was then colder than afterwards. In London the summers were sensibly warmer at the end of the eighteenth century than afterwards, which agrees with the case at Lund and Copenhagen. The average temperature of the year has remained constant, with the exception of London, where it seems to have fallen a little.[1]

TABLE VII.

Months.	Haparanda, 1802–1898.				Stockholm, 1799–1898.			
	Warmest.	Year.	Coldest.	Year.	Warmest.	Year.	Coldest.	Year.
Jan.	−4°·1	1887	−22°·3	1809	1°·9	1873	−14°·2	1814
Feb.	−3·9	1822, 1891	−24·3	1871	2·7	1822	−12·8	1799
March	−1·8	1822	−15·6	1853	4·5	1822	−8·3	1888
April	1·6	1844	−7·8	1809	7·5	1803	−1·3	1812, 1829
May	9·2	1897	−4·6	1810	12·4	1889	3·2	1867
June	18·6	1810	7·0	1821	17·6	1826	10·6	1805
July	20·8	1815	11·8	1812	21·4	1855	12·9	1832
Aug.	19·4	1815	8·7	1833	20·9	1846	12·0	1864
Sept.	12·6	1815	1·8	1832	15·4	1824	8·0	1830
Oct.	6·3	1805	−4·6	1819, 1864, 1880	10·6	1821	0·7	1880
Nov.	1·1	1883	−12·2	1842	5·3	1822	−3·0	1829
Dec.	(0·5?)	1809	−19·6	1835	2·7	1857	−8·0	1817

Months.	Lund, 1753–1898.				London, 1763–1898.			
	Warmest.	Year.	Coldest.	Year.	Warmest.	Year.	Coldest.	Year.
Jan.	4°·0	1796	−9°·5	1809	8°·4	1796	−3°·4	1795
Feb.	3·3	1779	−10·4	1845	9·9	1779	−1·7	1895
March	4·3	1846	−7·7	1845	9·4	1780	0·9	1785
April	7·8	1778	1·2	1779	13·4	1783	4·2	1837
May	14·6	1773	6·9	1843	17·5	1784	8·8	1882
June	19·2	1889	11·6	1800	19·9	1846	12·6	1814
July	(21·2)	1826	13·9	1898	23·4	1783	14·7	1767
Aug.	20·9	1834	13·0	1864	21·1	1783	14·2	1816
Sept.	16·3	1775	9·2	1812	18·7	1784	11·1	1763
Oct.	11·6	1846	(2·1?)	1805	15·1	1811	6·7	1817
Nov.	7·2	1772	−3·2	1773	9·9	1783	3·3	1870
Dec.	4·3	1843	−9·2	1788	8·8	1806	−1·6	1890

[1] There is also another phenomenon, exactly observed during more than 130 years, which seems to indicate that the date when spring begins, and the average temperature of this season, have not sensibly changed during this time in middle Sweden. In fact, Appelberg has calculated that the mean date of the highest vernal flood of the river Dalelfven was May 29 during the years 1765-1830, and May 28 during the years 1831-94. Ossian Appelberg,

Whether the climatic variations during the last 100 or 150 years here considered are periodic, progressive, or accidental cannot yet be decided. How considerable the accidental variations of the mean temperature of a month are, results from the following Table containing the mean temperature of the warmest and coldest months that have occurred during the interval of years in question at Haparanda, Stockholm, Lund, London, and Paris.

Months.	Paris, 1806–1898.[3]			
	Warmest.	Year.	Coldest.	Year.
Jan.	7·1°	1834	−4·4°	1838
Feb.	7·8	1809, 1869	−3·6	1895
March	10·2	1880	1·3	1845
April	15·1	1865	5·7	1837
May	17·7	1808, 1868	10·6	1879
June	21·2	1822	15·0	1823, 1854
July	22·7	1859	15·5	1816
Aug.	22·5	1842	15·5	1844
Sept.	19·7	1895	13·0	1807, 1877
Oct.	14·7	1831	7·3	1817
Nov.	10·6	1852	3·1	1858, 1871
Dec.	8·7	1806	−7·4	1879

Thus from the review now made of the variations of the climate in Western and North-Western Europe during the last thousand years no certain conclusion can be drawn, yet there seems to be some probability for a secular or long-period variation still going on from a more continental to a more maritime climate. If such be the case, it cannot, however, depend on the climatic variation above treated, which is produced by the variation of the obliquity of the ecliptic. For a thousand years is too short a space of time to produce any sensible variation attributable to this cause. Also the variation would then appear principally in the climate of the summer, and would be almost insensible in that of the winter, whereas, according to the observations, the inverse is the case.

As the regular measurements of rain were begun in Sweden somewhat earlier than the observations of temperature,[1] one might believe that a comparison between older and newer measurements of rain would show some variation corresponding to that of the temperature. But by a nearer inspection we find that the older measurements of the rain evidently give too low values, either owing to an unsuitable mounting of the rain gauge or to negligence in the measurement. The latter seems to have been the case at Upsala, where the results before 1836 are nearly worthless; the former at Lund, where the rain gauge till 1867 was placed on the roof of the observatory. Thus only in a far distant future will it be possible to discover by means of measurements

"Om orsakerna till vattendragens naturliga vattenvariation" ("On the Causes of the Natural Variation of the Water in Currents"), *Teknisk Tidskrift*. Stockholm, 1896 and 1897.

[1] At Lund the measurement of rainfall was begun in 1748.

of the rain climatic variations which are possibly going on with regard to this element.

8. *Conclusion—Probable variations of the climate in the future.*

The above inquiry has shown that the principal variations of the climate of the past, comprising a space of time of at least one hundred and perhaps one thousand million years, are probably due to long periodical, and perhaps also accidental, variations of the quantity of carbonic acid in the atmosphere, whereas the insolation during all this time has been nearly constant, except during the primeval epoch, when it might have been increasing somewhat.

Smaller climatic variations have occurred owing to purely astronomical causes. Among these, that due to the variation of the obliquity of the ecliptic has left obvious traces in the geological history of the earth during the post-glacial time—a space of time of about fifty thousand years. Owing to this cause, about nine thousand years ago there was a warm summer period in the Arctic and northern regions, and since that time the summers have become gradually cooler. This deterioration of our climate will continue during the next ten thousand years. The amplitude of this variation amounts to some 4° C. at 60° N.

Finally, a review of the historical reports during the last thousand years has led, with some probability, to the conclusion that a climatic variation is going on from a more continental to a more maritime climate in the north-west of Europe, especially in Scandinavia and Great Britain. The character in other respects and the cause of this variation are unknown. We cannot say if the variation is periodical, progressive, or accidental, nor how far it extends in space and time.

Now if, guided by the above results, we ask what the future climate of our earth will be, the answer runs as follows:—

The sun must at some time lose its capacity of radiating heat, owing to its continual spending of its energy. The sun, according to Helmholtz's theory, maintains its heat by contracting, and thereby becomes always hotter. My calculation[1] has given the result that its mean temperature is at present between four million and two hundred million centigrade degrees, and that the present thermometrical heat store of the sun is probably more than fifty million centigrade calories per unit of mass. Also there is probably still a considerable store of potential energy which is being gradually changed to radiant heat. But as the sun contracts, its mass becomes still more viscous, and this viscosity probably opposes a still increasing obstacle to the convectional currents which carry the interior heat to the surface. This latter, losing incessantly an enormous quantity of heat by radiation, must begin to cool as soon as, owing to this obstacle, the heat supply from the interior becomes insufficient to maintain the surface temperature. How long this will last, till this state of gradual cooling will begin, we cannot say, but probably the insolation will be sufficient still for many million years to supply the earth with radiant heat sufficient for life.

Also, as we have shown that the carbonic acid in the atmosphere is an essential condition for life on the earth, and that the carbonic acid is

[1] N. Ekholm, *Ueber den Energievorrath*, etc., cited above.

incessantly consumed by the chemical processes going on at the earth's surface and supplied principally by volcanic activity, we may ask how long this supply might be sufficient.

Now, as shown above, the volcanic activity is maintained by the secular cooling of the earth and the gradual, though periodical and partly irregular, contraction caused thereby. The volcanic activity will thus continue as long as the inner heat of the earth has not sunk sensibly below its present value. But we have found above that the cooling of the earth is extremely slow, for it takes probably about ten million years before the mean temperature of the earth has fallen 1° C. And as this temperature, if we judge from the volcanic eruptions, is still at least 2000° C., and according to the estimates of modern geophysicists even much higher, we conclude that the volcanic activity on the earth will probably continue with nearly the same intensity as at present during many hundred million years, thus probably much longer than the solar radiation. Thus we have nothing to fear for the existence of life on the earth from a future want of volcanic activity.

Yet we must expect that secular variations of the quantity of carbonic acid in the atmosphere will occur and cause climatic variations of the same kind as those revealed by geological science. Thus a future Ice Age might possibly occur. But here we find a remarkable circumstance that has hitherto been unexampled in the history of the earth. This is the influence of Man on climate.

In fact, we have seen that the present burning of pit-coal is so great that in one year it gives back to the atmosphere about $\frac{1}{1000}$ of its present store of carbonic acid. If this continues for some thousand years it will undoubtedly cause a very obvious rise of the mean temperature of the earth. Also Man will no doubt be able to increase the supply of carbonic acid also by digging of deep fountains pouring out carbonic acid. Further, it might perhaps be possible for Man to diminish or regulate the consumption of carbonic acid by protecting the weathering layers of silicates from the influence of the air and by ruling the growth of plants according to his wants and purposes. Thus it seems possible that Man will be able efficaciously to regulate the future climate of the earth and consequently prevent the arrival of a new Ice Age. By such means also the deterioration of the climate of the northern and Arctic regions, depending on the decrease of the obliquity of the ecliptic, may be counteracted. It is too early to judge of how far Man might be capable of thus regulating the future climate. But already the view of such a possibility seems to me so grand that I cannot help thinking that it will afford to Mankind hitherto unforeseen means of evolution.

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