Svante Arrhenius (1859-1927)

"On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground"

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I. Introduction: Observations of *Langley* on Atmospherical Absorption

A great deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall[2] in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variation of the temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this: Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier[3] maintained that the atmosphere acts like the glass of a hot-house, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet[4]; and Langley was by some of his researches led to the view, that "the temperature of the earth under direct sunshine, even though our atmosphere were present as now, would probably fall to -200°C., if that atmosphere did not possess the quality of selective absorption"[5]. This view, which was founded on too wide a use of Newton's law of cooling, must be abandoned, as Langley himself in a later memoir showed that the full moon, which certainly does not posses any sensible heat-absorbing atmosphere, has a "mean effective temperature" of about 45°C. [6]

The air retains heat (light or dark) in two different ways. On the one hand, the heat suffers a selective diffusion on its passage through the air; on the other hand, some of the atmospheric gases absorb considerable quantities of heat. These two actions are very different. ...

The selective absorption of the atmosphere is, according to the researches of Tyndall, Lecher and Pernter, Röntgen, Heine, Langley, Ångström, Paschen, and others[7], of a wholly different kind. It is not exerted by the chief mass of the air, but in a high degree by aqueous vapour and carbonic acid, which are present in the air in small quantities. Further, this absorption is not continuous over the whole spectrum, but nearly insensible in the light part of it, and chiefly limited to the long-waved part, where it manifests itself in very well-defined absorption-bands, which fall off rapidly on both sides[8]. The influence of this absorption is comparatively small on the heat from the sun, but must be of great importance in the transmission of rays from the earth. Tyndall held the opinion that the water-vapour has the greatest influence, whilst other authors, for instance Lecher and Pernter, are inclined to think that the carbonic acid plays the more important part. The researches of Paschen show that these gases are both very effective, so that probably sometimes the one, sometimes the other, may have the greater effect according to the circumstances.

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II. The Total Absorption by Atmospheres of Varying Composition

As we have now determined, in the manner described, the values of the absorption-coefficients for all kinds of rays, it will with the help of Langley's figures[9] be possible to calculate the fraction of the heat from a body at 15°C. (the earth) which is absorbed by an atmosphere that contains specified quantities of carbonic acid and water-vapour. ...

III. Thermal Equilibrium on the Surface and in the Atmosphere of the Earth

As we now have a sufficient knowledge of the absorption of heat by the atmosphere, it remains to examine how the temperature of the ground depends on the absorptive power of the air. Such an investigation has been already performed by Pouillet[10], but it must be made anew, for Pouillet used hypotheses that are not in agreement with our present knowledge.

In our deductions we will assume that the heat that is conducted from the interior of the earth to its surface may be wholly neglected. If a change occurs in the temperature of the earth's surface, the upper layers of the earth's crust will evidently also change their temperature; but this later process will pass away in a very short time in comparison with the time that is necessary for the alteration of the surface temperature, so that at any time the heat that is transported from the interior to the surface (positive in the winter, negative in the summer) must remain independent of the small secular variations of the surface temperature, and in the course of a year be very nearly equal to zero.

Likewise we will suppose that the heat that is conducted to a given place on the earth's surface or in the atmosphere in consequence of atmospheric or oceanic currents, horizontal or vertical, remains the same in the course of the time considered, and we will also suppose that the clouded part of the sky remains unchanged. It is only the variation of the temperature with the transparency of the air that we shall examine.

All authors agree in the view that there prevails an equilibrium in the temperature of the earth and of its atmosphere. The atmosphere must, therefore, radiate as much heat to space as it gains partly through the absorption of the sun's rays, partly through the radiation from the hotter surface of the earth and by means of ascending currents of air heated by contact with the ground. On the other hand, the earth loses just as much heat by radiation o space and to the atmosphere as it gains by absorption of the sun's rays. If we consider a given place in the atmosphere or on the ground, we must also take into consideration the quantities of heat that are carried to this place by means of oceanic or atmospheric currents. For this radiation we will suppose that Stefan's law of radiation, which is now generally accepted, holds good, or in other words that the quantity of heat (W) that radiates from a body of the albedo $(1-\nu)$ and temperature T (absolute) to another body of the absorption-coefficient β and absolute temperature θ is

$$W = \nu\beta\gamma(T^4-\theta^4),$$

where γ is the so-called radiation constant (1.21×10^{-12} per sec. and cm.^{2}) Empty space may be regarded as having the absolute temperature 0[11].

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IV. Calculation of the Variation of Temperature that would ensue in consequence of a given Variation of the Carbonic Acid in the Air.

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By means of these values, I have calculated the mean alteration of temperature that would follow if the quantity of carbonic acid varied from its present mean value (K=1) to another, viz. to K=0.67, 1.5, 2, 2.5, and 3 respectively. This calculation is made for every tenth parallel, and separately for the four seasons of the year. The variation is given in Table VII.

Table VII.--*Variation of Temperature caused by a given Variation of Carbonic Acid.*

[Editor's note: Arrhenius' Table VII actually consists of five tables side by side, each representing a different concentration of 'carbonic acid'. For ease of viewing, I have decoupled these tables. I have also written explicitly the latitude ranges, whereas the author placed the data between listed latitudes. CJG]

Carbonic Acid=0.67.

Latitude.	Dec.-Feb.	March-May.	June-Aug.	Sept.-Nov.	Mean of the year.
60 to 70	-2.9	-3.0	-3.4	-3.1	-3.1
50 to 60	-3.0	-3.2	-3.4	-3.3	-3.22
40 to 50	-3.2	-3.3	-3.3	-3.4	-3.3
30 to 40	-3.4	-3.4	-3.2	-3.3	-3.32
20 to 30	-3.3	-3.2	-3.1	-3.1	-3.17
10 to 20	-3.1	-3.1	-3.0	-3.1	-3.07
0 to 10	-3.1	-3.0	-3.0	-3.0	-3.02
-10 to 0	-3.0	-3.0	-3.1	-3.0	-3.02
-10 to -20	-3.1	-3.1	-3.2	-3.1	-3.12
-20 to -30	-3.1	-3.2	-3.3	-3.2	-3.2
-30 to -40	-3.3	-3.3	-3.4	-3.4	-3.35
-40 to -50	-3.4	-3.4	-3.3	-3.4	-3.37
-50 to -60	-3.2	-3.3	--	--	--

Carbonic Acid=1.5.

Latitude.	Dec.-Feb.	March-May.	June-Aug.	Sept.-Nov.	Mean of the year.
60 to 70	3.3	3.4	3.8	3.6	3.52
50 to 60	3.4	3.7	3.6	3.8	3.62
40 to 50	3.7	3.8	3.4	3.7	3.65
30 to 40	3.7	3.6	3.3	3.5	3.52
20 to 30	3.5	3.3	3.2	3.5	3.47
10 to 20	3.5	3.2	3.1	3.2	3.25
0 to 10	3.2	3.2	3.1	3.1	3.15
-10 to 0	3.1	3.1	3.2	3.2	3.15
-10 to -20	3.2	3.2	3.2	3.2	3.2
-20 to -30	3.2	3.2	3.4	3.3	3.27
-30 to -40	3.4	3.5	3.7	3.5	3.52
-40 to -50	3.6	3.7	3.8	3.7	3.7
-50 to -60	3.8	3.7	--	--	--

Carbonic Acid=2.0.

Latitude.	Dec.-Feb.	March-May.	June-Aug.	Sept.-Nov.	Mean of the year.
60 to 70	6.0	6.1	6.0	6.1	6.05
50 to 60	6.1	6.1	5.8	6.1	6.02
40 to 50	6.1	6.1	5.5	6.0	5.92
30 to 40	6.0	5.8	5.4	5.6	5.7
20 to 30	5.6	5.4	5.0	5.2	5.3
10 to 20	5.2	5.0	4.9	5.0	5.02
0 to 10	5.0	5.0	4.9	4.9	4.95
-10 to 0	4.9	4.0	5.0	5.0	4.97
-10 to -20	5.0	5.0	5.2	5.1	5.07
-20 to -30	5.2	5.3	5.5	5.4	5.35
-30 to -40	5.5	5.6	5.8	5.6	5.62
-40 to -50	5.8	6.0	6.0	6.0	5.95
-50 to -60	6.0	6.1	--	--	--

Carbonic Acid=2.5.

Latitude.	Dec.-Feb.	March-May.	June-Aug.	Sept.-Nov.	Mean of the year.
60 to 70	7.9	8.0	7.9	8.0	7.95
50 to 60	8.0	8.0	7.6	7.9	7.87
40 to 50	8.0	7.9	7.0	7.9	7.7
30 to 40	7.9	7.6	6.9	7.3	7.42
20 to 30	7.2	7.0	6.6	6.7	6.87
10 to 20	6.7	6.6	6.3	6.6	6.52
0 to 10	6.6	6.4	6.3	6.4	6.42
-10 to 0	6.4	6.4	6.6	6.6	6.5
-10 to -20	6.6	6.6	6.7	6.7	6.65
-20 to -30	6.7	6.8	7.0	7.0	6.87
-30 to -40	7.0	7.2	7.4	7.4	7.32
-40 to -50	7.7	7.9	7.9	7.9	7.85
-50 to -60	7.9	8.0	--	--	--

Carbonic Acid=3.0.

Latitude.	Dec.-Feb.	March-May.	June-Aug.	Sept.-Nov.	Mean of the year.
60 to 70	9.1	9.3	9.4	9.4	9.3
50 to 60	9.3	9.5	8.9	9.5	9.3

40 to 50	9.5	9.4	8.6	9.2	9.17
30 to 40	9.3	9.0	8.2	8.8	8.82
20 to 30	8.7	8.3	7.5	7.9	8.1
10 to 20	7.9	7.5	7.2	7.5	7.52
0 to 10	7.4	7.	7.2	7.3	7.3
-10 to 0	7.3	7.3	7.4	7.4	7.35
-10 to -20	7.4	7.5	8.0	7.6	7.62
-20 to -30	7.9	8.1	8.6	8.3	8.22
-30 to -40	8.6	8.7	9.1	8.8	8.8
-40 to -50	9.1	9.2	9.4	9.3	9.25
-50 to -60	9.4	9.5	--	--	--

A glance at this Table shows that the influence is nearly the same over the whole earth. The influence has a minimum near the equator, and increases from this to a flat maximum that lies the further from the equator the higher the quantity of carbonic acid in the air. For K=0.67 the maximum effect lies about the 40th parallel, for K=1.5 on the 50th, for K=2 on the 60th, and for higher K-values above the 70th parallel. The influence is in general greater in the winter than in the summer, except in the case of the parts that lie between the maximum and the pole. The influence will also be greater the higher the value of ν, that is in general somewhat greater for land than for ocean. On account of the nebulosity of the Southern hemisphere, the effect will be less there than in the Northern hemisphere. An increase in the quantity of carbonic acid will of course diminish the difference in temperature between day and night. A very important secondary elevation of the effect will be produced in those places that alter their albedo by the extension or regression of the snow-covering (see p. 257 [omitted from this excerpt--CJG]), and this secondary effect will probably remove the maximum effect from lower parallels to the neighbourhood of the poles[12].

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We may now inquire how great must the variation of the carbonic acid in the atmosphere be to cause a given change of the temperature. The answer may be found by interpolation in Table VII. To facilitate such an inquiry, we may make a simple observation. If the quantity of carbonic acid decreases from 1 to 0.67, the fall of temperature is nearly the same as the increase of temperature if this quantity augments to 1.5. And to get a new increase of this order of magnitude (3°.4), it will be necessary to alter the quantity of carbonic acid till it reaches a value nearly midway between 2 and 2.5. Thus if the quantity of carbonic acid increases in geometric progression, the augmentation of the temperature will increase nearly in arithmetic progression. This rule--which naturally holds good only in the part investigated--will be useful for the following summary estimations.

5. Geological Consequences.

I should certainly not have undertaken these tedious calculations if an extraordinary interest had not been connected with them. In the Physical Society of Stockholm there have been occasionally very lively discussions on the probable causes of the Ice Age; and these discussions have, in my opinion, led to the conclusion that there exists as yet no satisfactory hypothesis that could explain how the climatic conditions for an ice age could be realized in so short a time as that which has elapsed from the days of the glacial

epoch. The common view hitherto has been that the earth has cooled in the lapse of time; and if one did not know that the reverse has been the case, one would certainly assert that this cooling must go on continuously. Conversations with my friend and colleague Professor Högbom, together with the discussions above referred to, led me to make a preliminary estimate of the probable effect of a variation of the atmospheric carbonic acid on the belief that one might in this way probably find an explanation for temperature variations of 5°-10°C., I worked out the calculation more in detail, and lay it now before the public and the critics.

From geological researches the fact is well established that in Tertiary times there existed a vegetation and an animal life in the temperate and arctic zones that must have been conditioned by a much higher temperature than the present in the same regions.[13] The temperature in the arctic zones appears to have exceeded the present temperature by about 8 or 9 degrees. To this genial time the ice age succeeded, and this was one or more times interrupted by interglacial periods with a climate of about the same character as the present, sometimes even milder. When the ice age had its greatest extent, the countries that now enjoy the highest civilization were covered with ice. This was the case with Ireland, Britain (except a small part in the south), Holland, Denmark, Sweden and Norway, Russia (to Kiev, Orel, and Nijni-Novgorod), Germany and Austria (to the Harz, Erz-Gebirge, Dresden, and Cracow). At the same time an ice-cap from the Alps covered Switzerland, parts of France, Bavaria south of the Danube, the Tyrol, Styria, and other Austrian countries, and descended into the northern part of Italy. Simultaneously, too, North America was covered with ice on the west coast to the 47th parallel, on the east coast to the 40th, and in the central part to the 37th (confluence of the Mississippi and Ohio rivers). In the most different parts of the world, too, we have found traces of a great ice age, as in the Caucasus, Asia Minor, Syria, the Himalayas, India, Thian Shan, Altai, Atlas, on Mount Kenia and Kilimandjaro (both very near to the equator), in South Africa, Australia, New Zealand, Kerguelen, Falkland Islands, Patagonia and other parts of South America. The geologists in general are inclined to think that these glaciations were simultaneous on the whole earth[14]; and this most natural view would probably have been generally accepted, if the theory of Croll, which demands a genial age on the Southern Hemisphere at the same time as an ice age on the Northern and *vice versa*, had not influenced opinion. By measurements of the displacement of the snow-line we arrive at the result,--and this is very concordant for different places-- that the temperature at that time must have been 4°-5°C. lower than at present. The last glaciation must have taken place in rather recent times, geologically speaking, so that the human race certainly had appeared at that period. Certain American geologists hold the opinion that since the close of the ice age only some 7000 to 10,000 years have elapsed, but this most probably is greatly underestimated.

One may now ask, How much must the carbonic acid vary according to our figures, in order that the temperature should attain the same values as in the Tertiary and Ice ages respectively? A simple calculation shows that the temperature in the arctic regions would rise about 8° to 9°C., if the carbonic acid increased to 2.5 or 3 times its present value. In order to get the temperature of the ice age between the 40th and 50th parallels, the carbonic acid in the air should sink to 0.62--0.55 of its present value (lowering of temperature 4°-5°C.). The demands of the geologists, that at the genial epochs the climate should be more uniform than now, accords very well with our theory. The geographical annual and diurnal ranges of temperature would be partly smoothed away, if the quantity of carbonic acid was augmented. The reverse would be the case (at least to a latitude of 50 from the equator), if the carbonic acid diminished in amount. But in both these cases I incline to think that the secondary action (see p. 257 [omitted from this excerpt--CJG]) due to the regress or the progress of the snow-covering would play the most important role. The theory demands also that, roughly speaking, the whole earth should have undergone about the same variations of temperature, so that according to it genial or glacial epochs must have occurred simultaneously on the whole earth. Because of the greater nebulosity of the Southern hemisphere, the variations must there have been a little less (about 15 per cent.) than in the Northern hemisphere. The ocean currents, too, must there, as in the present time, have effaced the

differences in temperature at different latitudes to a greater extent than in the Northern hemisphere. This effect also results from the greater nebulosity in the arctic zones than in the neighbourhood of the equator.

There is now an important question which should be answered, namely:--Is it probable that such great variations in the quantity of carbonic acid as our theory requires have occurred in relatively short geological times? The answer to this question is given by Prof. Högbom. As his memoir on this question may not be accessible to most readers of these pages, I have summed up an translated his utterances which are of most importance to our subject[15]:--

"Although it is not possible to obtain exact quantitative expressions for the reactions in nature by which carbonic acid is developed or consumed, nevertheless there are some factors, of which one may get an approximately true estimate, and from which certain conclusions that throw light on the question may be drawn. In the first place, it seems to be of importance to compare the quantity of carbonic acid now present in the air with the quantities that are being transformed. If the former is insignificant with the latter, then the probability for variations is wholly other than in the opposite case.

"On the supposition that the mean quantity of carbonic acid in the air reaches 0.03 vol. per cent., this number represents 0.045 per cent. by weight, or 0.342 millim. partial pressure, or 0.466 gramme of carbonic acid for every cm.^{2} of the earth's surface. The quantity of carbon that is fixed in the living organic world can certainly not be estimated with the same degree of exactness; but it is evident that the numbers that might express this quantity ought to be of the same order of magnitude, so that the carbon in the air can neither be conceived of as very great nor as very little, in comparison with the quantity of carbon occurring in organisms. With regard to the great rapidity with which the transformation in organic nature proceeds, the disposable quantity of carbonic acid is not so excessive that changes caused by climatological or other reasons in the velocity and value of that transformation might be not able to cause displacements of the equilibrium.

"The following calculation is also very instructive for the appreciation of the relation between the quantity of carbonic acid in the air and the quantities that are transformed. The world's present production of coal reaches in round numbers 500 millions of tons per annum, or 1 ton per km.^{2} of the earth's surface. Transformed into carbonic acid, this quantity would correspond to about a thousandth part of the carbonic acid in the atmosphere. It represents a layer of limestone of 0.003 millim. thickness over the whole globe, or 1.5 km.^{3} in cubic measure. This quantity of carbonic acid, which is supplied to the atmosphere chiefly by modern industry, may be regarded as completely compensating the quantity of carbonic acid that is consumed in the formation of limestone (or other mineral carbonates) by the weathering or decomposition of silicates. From the determination of the amounts of dissolved substances, especially carbonates, in a number of rivers in different countries and climates, and of the quantity of water flowing in these rivers and of their drainage-surface compared with the land-surface of the globe, it is estimated that the quantities of dissolved carbonates that are supplied to the ocean in the course of a year reach at most the bulk of 3 km.^{3} As it is also proved that the rivers the drainage regions of which consist of silicates convey very unimportant quantities of carbonates compared with those that flow through limestone regions, it is permissible to draw the conclusion, which is also strengthened by other reasons, that only an insignificant part of these 3 km.^{3} of carbonates is formed directly by decomposition of silicates. In other words, only an unimportant part of this quantity of carbonate of lime can be derived from the process of weathering in a year. Even though the number given were on account of inexact or uncertain assumptions erroneous to the extent of 50 per cent. or more, the comparison instituted is of very great interest, as it proves that the most important of all the processes by means of which carbonic acid has been removed from the atmosphere in all times, namely the chemical weathering of

siliceous minerals, is of the same order of magnitude as a process of contrary effect, which is caused by the industrial development of our time, and which must be conceived of as being of a temporary nature.

"In comparison with the quantity of carbonic acid which is fixed in limestone (and other carbonates), the carbonic acid of the air vanishes. With regard to the thickness of sedimentary formations and the great part of them that is formed by limestone and other carbonates, it seems not improbable that the total quantity of carbonates would cover the whole earth's surface to a height of hundreds of metres. If we assume 100 metres,- a number that may be inexact in a high degree, but probably is underestimated,--we find that about 25,000 times as much carbonic acid is fixed to lime in the sedimentary formations as exists free in the air. Every molecule of carbonic acid in this mass of limestone has, however, existed in and passed through the atmosphere in the course of time. Although we neglect all other factors which may have influenced the quantity of carbonic acid in the air, this number lends but very slight probability to the hypothesis, that this quantity should in former geological epochs have changed within limits which do not differ much from the present amount. As the process of weathering has consumed quantities of carbonic acid many thousand times greater than the amount now disposable in the air, and as this process from different geographical, climatological and other causes has in all likelihood proceeded with very different intensity at different epochs, the probability of important variations in the quantity of carbonic acid seems to be very great, even if we take into account the compensating processes which, as we shall see in what follows, are called forth as soon as, for one reason or another, the production or consumption of carbonic acid tends to displace the equilibrium to any considerable degree. One often hears the opinion expressed, that the quantity of carbonic acid in the air ought to have been very much greater formerly than now, and that the diminution should arise from the circumstance that carbonic acid has been taken from the air and stored in the earth's crust in the form of coal and carbonates. In many cases this hypothetical diminution is ascribed only to the formation of coal, whilst the much more important formation of carbonates is wholly overlooked. This whole method of reasoning on a continuous diminution of the carbonic acid in the air loses all foundation in fact, notwithstanding that enormous quantities of carbonic acid in the course of time have been fixed in carbonates, if we consider more closely the processes by means of which carbonic acid has in all times been supplied to the atmosphere. From these we may well conclude that enormous variations have occurred, but not that the variation has always proceeded in the same direction.

"Carbonic acid is supplied to the atmosphere by the following processes:--(1) volcanic exhalations and geological phenomena connected therewith; (2) combustion of carbonaceous meteorites in the higher regions of the atmosphere; (3) combustion and decay of organic bodies; (4) decomposition of carbonates; (5) liberation of carbonic acid mechanically inclosed in minerals on their fracture or decomposition. The carbonic acid of the air is consumed chiefly by the following processes:--(6) formation of carbonates from silicates on weathering; and (7) the consumption of carbonic acid by vegetative processes. The ocean, too, plays an important role as a regulator of the quantity of carbonic acid in the air by means of the absorptive power of its water, which gives off carbonic acid as its temperature rises and absorbs it as it cools. The processes named under (4) and (5) are of little significance, so that they may be omitted. So too the processes (3) and (7), for the circulation of matter in the organic world goes on so rapidly that their variations cannot have any sensible influence. From this we must except periods in which great quantities of organisms were stored up in sedimentary formations and thus subtracted from the circulation, or in which such stored-up products were, as now, introduced anew into the circulation. The source of carbonic acid named in (2) is wholly incalculable.

"Thus the processes (1), (2), and (6) chiefly remain as balancing each other. As the enormous quantities of carbonic acid (representing a pressure of many atmospheres) that are now fixed in the limestone of the earth's

crust cannot be conceived to have existed in the air but as an insignificant fraction of the whole at any one time since organic life appeared on the globe, and since therefore the consumption through weathering and formation of carbonates must have been compensated by means of continuous supply, we must regard volcanic exhalations as the chief source of carbonic acid for the atmosphere.

"But this source has not flowed regularly and uniformly. Just as single volcanoes have their periods of variation with alternating relative rest and intense activity, in the same manner the globe as a whole seems in certain geological epochs to have exhibited a more violent and general volcanic activity, whilst other epochs have been marked by a comparative quiescence of the volcanic forces. It seems therefore probable that the quantity of carbonic acid in the air has undergone nearly simultaneous variations, or at least that this factor has had an important influence.

"If we pass the above-mentioned processes for consuming and producing carbonic acid under review, we find that they evidently do not stand in such a relation to or dependence on one another that any probability exists for the permanence of an equilibrium of the carbonic acid in the atmosphere. An increase or decrease of the supply continued during geological periods must, although it may not be important, conduce to remarkable alterations of the quantity of carbonic acid in the air, and there is no conceivable hindrance to imagining that this might in a certain geological period have been several times greater, or on the other hand considerably less, than now."

As the question of the probability of quantitative variation of the carbonic acid in the atmosphere is in the most decided manner answered by Prof. Högbom, there remains only one other point to which I wish to draw attention in a few words, namely: Has no one hitherto proposed any acceptable explanation for the occurrence of genial and glacial periods? Fortunately, during the progress of the foregoing calculations, a memoir was published by the distinguished Italian meteorologist L. De Marchi which relieves me from answering the last question[16]. He examined in detail the different theories hitherto proposed- -astronomical, physical, or geographical, and of these I here give a short *résumé*. These theories assert that the occurrence of genial or glacial epochs should depend on one or other change in the following circumstances:--

1. The temperature of the earth's place in space.
2. The sun's radiation to the earth (solar constant).
3. The obliquity of the earth's axis to the ecliptic.
4. The position of the poles on the earth's surface.
5. The form of the earth's orbit, especially its eccentricity (Croll).
6. The shape and extension of continents and oceans.
7. The covering of the earth's surface (vegetation).
8. The direction of the oceanic and aerial currents.
9. The position of the equinoxes.

De Marchi arrives at the conclusion that all these hypotheses must be rejected (p. 207). On the other hand, he is of the opinion that a change in the transparency of the atmosphere would possibly give the desired effect. According to his calculations, "a lowering of this transparency would effect a lowering of the temperature on the whole earth, slight in the equatorial regions, and increasing with the latitude into the 70th parallel, nearer the poles again a little less. Further, this lowering would, in non-tropical regions, be less on the continents than on the ocean and would diminish the annual variations of the temperature. This diminution of the air's transparency ought chiefly to be attributed to a greater quantity of aqueous vapour in the air, which would cause not only a direct cooling but also copious precipitation of water and snow on the continents. The origin of this greater quantity of water- vapour is not easy to explain." De Marchi has arrived at wholly other results

than myself, because selective absorption which is possessed by aqueous vapour. And, further, he has forgotten that if aqueous vapour is supplied to the atmosphere, it will be condensed till the former condition is reached, if no other change has taken place. As we have seen, the mean relative humidity between the 40th and 60th parallels on the northern hemisphere is 76 per cent. If, then, the mean temperature sank from its actual value +5.3 by 4°-5°C., *i. e*. to +1.3 or +0.3, and the aqueous vapour remained in the air, the relative humidity would increase to 101 or 105 per cent. This is of course impossible, for the relative humidity cannot exceed 100 per cent. in the free air. *A fortiori* it is impossible to assume that the absolute humidity could have been greater than now in the glacial epoch.

As the hypothesis of Croll still seems to enjoy a certain favour with English geologists, it may not be without interest to cite the utterance of De Marchi on this theory, which he, in accordance with its importance, has examined more in detail than the others. He says, and I entirely agree with him on this point:--"Now I think I may conclude that from the point of view of climatology or meteorology, in the present state of these sciences, the hypothesis of Croll seems to be wholly untenable as well in its principles as in its consequences" [17].

It seems that the great advantage which Croll's hypothesis promised to geologists, viz. of giving them a natural chronology, predisposed them in favour of its acceptance. But this circumstance, which at first appeared advantageous, seems with the advance of investigation rather to militate against the theory, because it becomes more and more impossible to reconcile the chronology demanded by Croll's hypothesis with the facts of observation.

I trust that after the foregoing pages will prove useful in explaining some points in geological climatology which have hitherto proved most difficult to interpret.

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[1] Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December, 1895. Communicated by the Author.

[2] 'Heat a Mode of Motion', 2nd ed. p. 405 (Lond., 1865).

[3] *Mém. de l'Ac. R. d. Sci. de l'Inst. de France*, t. vii. 1827.

[4] *Comptes rendus*, t. vii. p. 41 (1838).

[5] Langley, 'Professional Papers of the Signal Service,' No. 15. "Researches on Solar Heat," p. 123 (Washington, 1884).

[6] Langley, "The Temperature of the Moon," Mem. of the National Academy of Sciences, vol. iv, 9th mem. p. 193 (1890).

[7] Vide Winkelmann, *Handbuch der Physik*.

[8] Cf., e.g., Trabert, *Meteorologische Zeitschrift*, Bd. ii. p. 238 (1894).

[9] 'Temperature of the Moon,' plate 5.

[10] Pouillet, *Comptes rendus*, t. vii. p. 41 (1838).

[11] Langley, 'Prof. Papers,' No. 15, p. 122. "The Temperature of the Moon," p. 206.

[12] See Addendum, p. 275. [Omitted from this excerpt.--CJG]

[13] For details *cf*. Neumayr, *Erdgeschichte*, Bd. 2, Leipzig, 1887; and Geikie, "The Great Ice-Age,' 3rd ed. London, 1894; Nathorst, *Jirdens historia*, p. 989, Stockholm, 1894.

[14] Neumayr, *Erdgeschichte*, p. 648; Nathorst, *l. c*. p. 992.

[15] Högbom, *Svensk kemisk Tidskrift*, Bd. vi. p. 169 (1894).

[16] Luigi De Marchi: *Le cause dell'era glaciale*, premiato dal R. Istituto Lombardo, Pavia, 1895.

[17] De Marchi, *l. c*. p. 166.