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ON THE INFLUENCE OF CARBONIC ACID IN THE AIR UPON THE TEMPERATURE OF THE GROUND

In 1896, Swedish Nobel Laureate chemist Svante Arrhenius revisited Tyndall's idea that the absorption of energy by water vapor and CO_2 might help regulate the temperature of the earth. Depressed after an acrimonious divorce and an unsuccessful bid for custody of his son, Arrhenius set to work on a tedious set of mathematical calculations based on the absorption coefficients of gases to create a pencil-and-paper model of the influence of atmospheric CO_2 on the temperature of the earth at various latitudes. Arrhenius was most concerned with using the model to suggest that reduced atmospheric CO_2 accompanied—and potentially caused—the then recently discovered ice age of the geologic past. But his tables and discussion here also reveal temperature predictions for a world of rising CO_2—predictions that have earned him a place among the so-called forefathers of climate science. How does Arrhenius interpret Tyndall in this paper? What is familiar and what is strange about the way he deals with "carbonic acid"?*

Svante Arrhenius, "On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground," *Philosophical Magazine and Journal of Science* 5, no. 41 (April 1896): 237–76. Excerpt: pp. 237–38, 239, 263–69.

* For more on Arrhenius, see James R. Fleming, "John Tyndall, Svante Arrhenius, and Early Research on Carbon Dioxide and Climate," in *Historical Perspectives on Climate Change* (New York: Oxford University Press, 1998), 8:65–68. Arrhenius expanded upon the potential benefits of CO_2-induced warming in a later popular work, *Worlds in the Making: The Evolution of the Universe* (New York: Harper, 1908).

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 in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of the temperature that were lessened by this circumstance. Another side of the question, that long has 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 maintained that the atmosphere acts like the glass of a hothouse, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet; 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." . . .

. . . Tyndall held the opinion that the water-vapour has the greatest influence, whilst other authors, for instance Lecher and Penter, 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. . . .

IV. Calculation of the Variation of Temperature that Would Ensue in the Consequences of a Given Variation of the Carbonic Acid in the Air

We now possess all the necessary data for an estimation of the effect on the earth's temperature which would be the result of a given variation of the aerial carbonic acid. . . .

In order to obtain values for the temperature for the whole earth, I have calculated from Dr. Buchan's charts of the mean temperature at different places in every month the mean temperature in every district

TABLE VI.—*Mean Temperature, Relative and Absolute Humidity**.

Latitude.	Mean Temperature.					Mean Relative Humidity.					Mean Absolute Humidity.				
	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
70–60	−21·1	− 8·3	+ 7·5	− 6·0	− 7·0	86	81	77	84	82	1·15	2·14	6·22	2·84	3·09
60–50	−11·2	+ 0·2	+13·5	+ 2·2	+ 1·2	83	74	76	80	78·2	2·22	3·82	8·82	4·7	4·9
50–40	− 1·4	+ 7·8	+18·7	+ 9·7	+ 8·7	78	73	69	76	74	3·86	5·98	10·8	7·16	6·95
40–30	+ 8·4	+14·5	+21·8	+16·6	+15·3	73	68	67	71	69·7	6·53	8·63	13·4	10·13	9·7
30–20	+17·0	+21·5	+26·0	+23·0	+21·9	71	68	70	73	70·5	10·36	12·63	17·1	15·0	13·8
20–10	+23·2	+25·5	+26·8	+25·9	+25·4	74	73	78	77	75·5	15·3	17·0	19·6	16·8	17·2
10–0	+25·5	+25·8	+25·4	+25·5	+25·5	77	78	82	81	79·5	17·7	18·9	19·9	19·3	18·9
0–−10	+25·7	+25·5	+24·0	+25·0	+25·1	81	81	82	80	81	19·4	19·0	17·9	18·3	18·7
−10–−20	+24·9	+24·0	+20·8	+23·1	+23·2	79	78	80	77	78·5	18·0	17·1	14·6	16·0	16·4
−20–−30	+22·4	+20·5	+16·4	+19·3	+19·7	75	79	80	75	77·2	14·8	14·0	11·1	13·0	13·2
−30–−40	+17·5	+15·2	+11·3	+14·2	+14·5	75	80	80	79	78·5	11·1	10·4	8·1	9·6	9·8
−40–−50	+11·6	+ 9·5	+ 5·9	+ 8·2	+ 8·7	81	81	83	79	81	8·34	7·08	5·94	6·63	6·99
−50–−60	+ 5·3	+ 2·0	− 0·4	+ 1·6	+ 2·1	83	79	—	—	—	5·74	4·46	—	—	—

* From the figures for temperature and relative humidity I have calculated the absolute humidity in grams per cubic metre.

that is contained between two parallels differing by 10 and two meridians, differing by 20 degrees (*e.g.* between 0° and 10° N. and 160° and 180° W).

By means of these values, I have calculated the mean alteration of the temperature that would follow if the quantity of carbonic acid varied from its present mean value (K = 1) to another, viz. to K = 0.671, 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.

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 the 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

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

Latitude.	Carbonic Acid=0·67. Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
70–60	−2·9	−3·0	−3·4	−3·1	−3·1
60–50	−3·0	−3·2	−3·4	−3·3	−3·22
50–40	−3·2	−3·3	−3·3	−3·4	−3·3
40–30	−3·4	−3·4	−3·2	−3·3	−3·32
30–20	−3·3	−3·2	−3·1	−3·1	−3·17
20–10	−3·1	−3·1	−3·0	−3·1	−3·07
10–0	−3·1	−3·0	−3·0	−3·0	−3·02
0–−10	−3·0	−3·0	−3·1	−3·0	−3·02
−10–−20	−3·1	−3·1	−3·2	−3·1	−3·12
−20–−30	−3·1	−3·2	−3·3	−3·2	−3·2
−30–−40	−3·3	−3·3	−3·4	−3·4	−3·35
−40–−50	−3·4	−3·4	−3·3	−3·4	−3·37
−50–−60	−3·2	−3·3	—	—	—

Latitude.	Carbonic Acid=1·5. Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
70–60	3·3	3·4	3·8	3·6	3·52
60–50	3·4	3·7	3·6	3·8	3·62
50–40	3·7	3·8	3·4	3·7	3·65
40–30	3·7	3·6	3·3	3·5	3·52
30–20	3·5	3·3	3·2	3·5	3·47
20–10	3·5	3·2	3·1	3·2	3·25
10–0	3·2	3·2	3·1	3·1	3·15
0–−10	3·1	3·1	3·2	3·2	3·15
−10–−20	3·2	3·2	3·2	3·2	3·2
−20–−30	3·2	3·2	3·4	3·3	3·27
−30–−40	3·4	3·5	3·7	3·5	3·52
−40–−50	3·6	3·7	3·8	3·7	3·7
−50–−60	3·8	3·7	—	—	—

Latitude.	Carbonic Acid=2·0. Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
70–60	6·0	6·1	6·0	6·1	6·05
60–50	6·1	6·1	5·8	6·1	6·02
50–40	6·1	6·1	5·5	6·0	5·92
40–30	6·0	5·8	5·4	5·6	5·7
30–20	5·6	5·4	5·0	5·2	5·3
20–10	5·2	5·0	4·9	5·0	5·02
10–0	5·0	5·0	4·9	4·9	4·95
0–−10	4·9	4·9	5·0	5·0	4·95
−10–−20	5·0	5·0	5·2	5·1	5·07
−20–−30	5·2	5·3	5·5	5·4	5·35
−30–−40	5·5	5·6	5·8	5·6	5·62
−40–−50	5·8	6·0	6·0	6·0	5·95
−50–−60	6·0	6·1	—	—	—

Latitude.	Carbonic Acid=2·5. Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
70–60	7·9	8·0	7·9	8·0	7·95
60–50	8·0	8·0	7·6	7·9	7·87
50–40	8·0	7·9	7·0	7·9	7·7
40–30	7·9	7·6	6·9	7·3	7·42
30–20	7·2	7·0	6·6	6·7	6·87
20–10	6·7	6·6	6·3	6·6	6·52
10–0	6·6	6·4	6·3	6·4	6·42
0–−10	6·4	6·4	6·6	6·6	6·5
−10–−20	6·6	6·6	6·7	6·7	6·65
−20–−30	6·7	6·8	7·0	7·0	6·87
−30–−40	7·0	7·2	7·7	7·4	7·32
−40–−50	7·7	7·9	7·9	7·9	7·85
−50–−60	7·9	8·0	—	—	—

Latitude.	Carbonic Acid=3·0. Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
70–60	9·1	9·3	9·4	9·4	9·3
60–50	9·3	9·5	8·9	9·5	9·3
50–40	9·5	9·4	8·6	9·2	9·17
40–30	9·3	9·0	8·2	8·8	8·82
30–20	8·7	8·3	7·5	7·9	8·1
20–10	7·9	7·5	7·2	7·5	7·52
10–0	7·4	7·3	7·2	7·3	7·3
0–−10	7·3	7·3	7·4	7·4	7·35
−10–−20	7·4	7·5	8·0	7·6	7·62
−20–−30	7·9	8·1	8·6	8·3	8·22
−30–−40	8·6	8·7	9·1	8·8	8·8
−40–−50	9·1	9·2	9·4	9·3	9·25
−50–−60	9·4	9·5	—	—	—

pole. The influence will also be greater the higher the value of *v*, 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), and this secondary effect will probably remove the maximum effect from lower parallels to the neighborhood of the poles. . . .

V. 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 Hogbom, 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 temperature of the earth. As this estimation led to the belief that one might in this way, probably find an explanation for temperature variation of 5°–10°C. I worked out the calculation in more 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. 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 at 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 50th, 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; and this most natural view would probably have been generally accepted if the theory of Croll, which demands a genial age of the Southern hemisphere at the same time as an ice age on the Northern and *vice versa*, had not influenced opinion. . . .

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°C 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°C–5°C.). . . .

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 time?