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Arrhenius' 1896 Model of the Greenhouse Effect in Context

Arrhenius' 1896 model of the influence of carbonic acid (CO_2) in the air on the temperature on the ground arose from debates concerning the causes of the Ice Ages in the Stockholm Physics Society. The calculation of the absorption-coefficients of H_2O and CO_2, which were the key to the construction of the model, was made possible through Arrhenius's use of Samuel P. Langley's measurements of heat emission in the lunar spectrum. The model enabled Arrhenius to show variations in mean temperature in sectors from 70°N to 60°S during four different seasons given five different levels of CO_2. The immediate reactions to the model concerned the question which Arrhenius had attempted to answer, i.e., the causes of the Ice Ages. Since the 1970s Arrhenius's work has received much wider attention due to the concern with global warming resulting from the burning of fossil fuels.

In early 1896, Svante Arrhenius published two articles presenting the first model of the influence of carbonic acid (CO_2) in the air on the temperature on the ground. One appeared in the *Supplement to the Proceedings of the Royal Swedish Academy of Sciences* (1), the other in the *Philosophical Magazine* (2). As he often did, Arrhenius had written similar articles in German and English, in order to make his work known to the two major scientific language groups of his time. The article in the *Philosophical Magazine* contained two distinct parts: the first presented computations allowing Arrhenius to predict the variations in temperature, which would result from variations of CO_2; the second discussed such variations as the cause of climatic change in geological times, especially the Ice Ages. This second part contained a translation from Swedish of part of an article by Arvid Högbom on the geological carbon cycle.

Arrhenius's articles did not conform to modern prescriptions for the presentation of the results of scientific work. The research question "Is the mean temperature on the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere?" and its status in the literature, were glossed over in the first paragraph. He then moved on to the computations involved in constructing the model. When he finally discussed the reasons for undertaking this work they were stated only in the vague terms of the "very lively discussions on the probable causes of the Ice Ages" that had taken place in the Stockholm Physics Society. Much of this can be explained by the haste with which Arrhenius completed this project, all of which, from inception to publication, only occupied him for a little over a year (December 1894 to January 1896). That he still managed to construct the first model of the influence of CO_2 on climate, makes it worth trying to understand how he arrived at it. This can be done by placing the work in context from: (i) what Arrhenius knew about research on heat-absorbing gases in the atmosphere and their influence on climate; and (ii) how he advanced such knowledge by his capacity to take advantage of data—in this case Samuel P. Langley's observations of the radiation received on earth from the moon—that could be used in support of his ideas. Hopefully, this will enable us to better understand the model and the conclusions that have been drawn from it, both in Arrhenius's time and later. However, it is necessary to be somewhat more explicit than Arrhenius to understand why he embarked on this work.


Arvid Högbom 1857–1940.

THE STOCKHOLM PHYSICS SOCIETY, CO_2 AND GLACIAL EPOCHS

In 1895, Arrhenius was 36-years old, but he had already left behind a career in physical chemistry. This career had started rather inauspiciously with his doctoral thesis on the conductivity of electrolytes, which he defended at Uppsala University in 1884 at the age of 25. Controversy with his professors and their uncomprehending attitudes toward the novelty of the ideas presented in the thesis led to its being awarded a very low grade. Basically, this put an end to Arrhenius's hopes for a career at Uppsala University. To gain research experience and also to have access to laboratory facilities he spent the next four years on the European continent, working at what we would today call postdoc level, but at the time his position in the laboratories of Wilhelm Ostwald in Leipzig, Ludwig Boltzmann in Graz, and J. H. van't Hoff in Amsterdam was much more diffuse. In 1887, at the age of 28 while at the Institute of Physics at the University of Würzburg, he formulated the hypothesis of ionic dissociation, the idea that electrolytes dissociate into their constituent ions, i.e. atoms or groups of atoms charged with positive or negative electricity, in very dilute solutions. In the next few years, his hypothesis matured into the theory of electrolytic dissociation, which spawned important new investigations on solutions and became one of the cornerstones of the new physical chemistry.

In 1891, Arrhenius returned permanently to Sweden having been appointed teacher of physics at the Stockholm Högskola (which later became the University of Stockholm). At the age of 32, he had secured his first stable employment. Although his reputation attracted foreign postgraduates who came to do work in physical chemistry at the Högskola, in the early 1890s, he gradually withdrew from active research in solution theory. In part, the reasons for this withdrawal were based on his feeling that physical chemistry was a field in which the most productive research topics had already been exploited. However, a more compelling reason was his involvement in the interdisciplinary research effort known as cosmic physics. This was an effort to bring the phenomena of the seas, atmosphere, and solid earth into the domain of the physical sci-

Waiting to take off for the North Pole in the summer of 1896. The balloonists (Nils Ekholm fourth from the left in the last row) entertain the crew of the vessel "Virgo" which had brought them to Spitsbergen. "Hydrographer" Arrhenius is seated on the table in the front row. Photo: Royal Swedish Academy of Sciences.

ences and to produce new theories taking into account the interrelatedness of terrestrial, atmospheric, and cosmic events. The task was facilitated by the rapid accumulation of data, often produced through new means—balloon ascents and spectroscopy applied in astrophysics, for instance—concerning all aspects of the earth and its atmosphere as well as the solar and lunar systems.

Cosmic physics was a product of the unique mix of persons and institutions that made up the Stockholm scientific milieu in the 1890s. At the center was the Stockholm Högskola a private, nondegree granting institution concentrating on science and natural history. It was here that Arrhenius became, first, a teacher of physics in 1891, then professor of physics in 1895 and, finally, rector in 1896. One of Arrhenius's first initiatives when he joined the Högskola faculty was to found the Stockholm Physics Society. The purpose of the Society was to meet fortnightly to hear lectures and engage in discussion concerning the latest advances in physics, broadly defined to include fields such as meteorology, geophysics, astrophysics, and physical chemistry. The Society met with immediate success. It soon drew to its meetings not only scientists from the Högskola but also those from other institutions, for instance, the Meteorological Office, the Swedish Geological Survey, and the Museum of Natural History. Among the core group, there was Arrhenius himself as Secretary of the Society, Otto Pettersson, Arvid Högbom, and Vilhelm Bjerknes, who were all professors at the Högskola, Nils Ekholm from the Meteorological Office, and S.A. Andrée from the Patent Office. In 1897, Andrée undertook an ill-fated attempt to reach the North Pole by balloon. Together they represented disciplines as diverse as physics, chemistry, mechanics, geology, and meteorology.

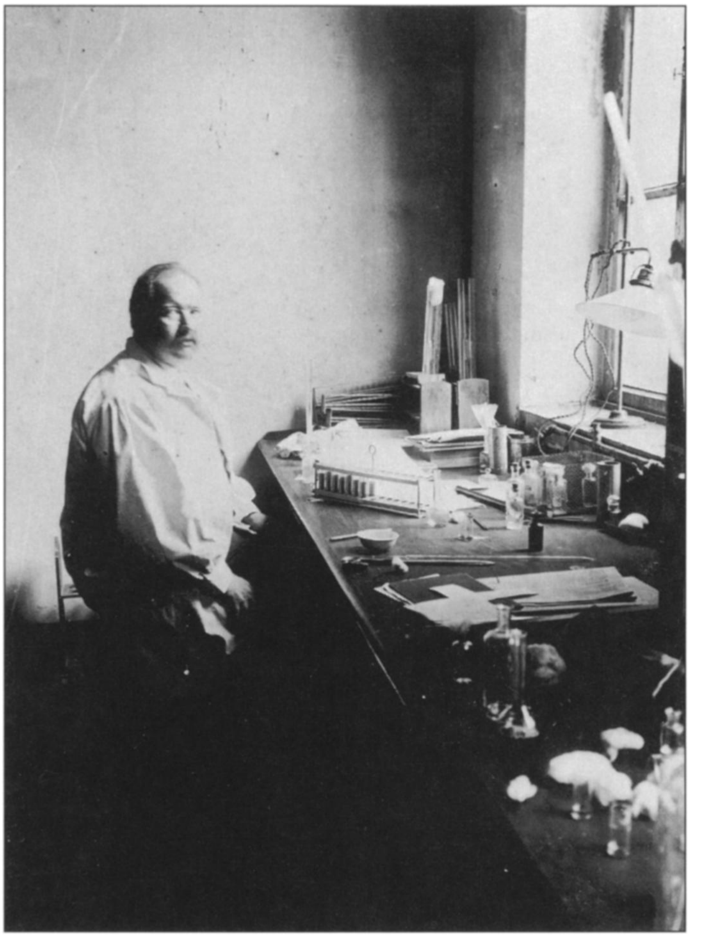
Cosmic physics in Stockholm was never institutionalized into teaching programs or chairs, but was practiced in the Society as a purely intellectual activity by persons who were, one might say, on leave from their home disciplines. As Arrhenius himself indicated in the article in *The Philosophical Magazine*, the discussions in the Physics Society stimulated him to construct the model. How this came about can be reconstructed from the minutes of the Physics Society and the articles about the debates that Arrhenius wrote for the daily papers. Two different strands of inquiry in the Society were involved, one concerned CO_2 and the other climatic change (3).

Starting in 1892, Pettersson, Andrée and Högbom gave lectures to the Society presenting fresh data on CO_2 on the ground, in the oceans and in the atmosphere. The lectures Högbom gave to the Physics Society in 1893 and to the Swedish Society of Chemists in 1894 were the most important, because they began to transform the problem of CO_2 from conjecture into theory (4). Högbom had originally become interested in CO_2 in the air as a geologist observing the formation and extension of limestone (the chief source of CO_2) across the globe. But he soon expanded his inquiry to include all the components of the geochemical cycle in which CO_2 is developed and consumed. His original contributions were to make estimates of the amount of CO_2 supplied to the atmosphere through different processes (what is now referred to as the geochemical carbon cycle) and to point to the buffering effects of the oceans. As for the short-term cycle, Högbom listed six ways in which atmospheric CO_2 is produced and three ways in which it is consumed. Among the former, i.e. production of CO_2, were volcanic exhalations, combustion and decay of organic bodies (especially burning of fossil fuels), and release of CO_2 dissolved in sea water because of increases in temperature. Among the latter, i.e. consumption of CO_2, were the formation of carbonates from silicates on weathering and the absorption of CO_2 in the sea.

The main thrust of Högbom's inquiry concerned the processes that may have caused variations in CO_2 on a geological time scale. He found that many of the processes making up the carbon cycle, for instance, combustion and decay of organic bodies or decomposition of carbonates, are either of little significance or go on so rapidly that their variation can not be of much consequence. Volcanic eruptions represented for him the one source that does not flow regularly and uniformly and can furthermore reach high levels of intensity. He concluded that even a small increase or decrease of the supply must lead to remarkable alterations of the quantity of CO_2 in the air. He saw no hindrance to imagining that this quantity might in a certain geological period have been several times greater or considerably less, than now.

The other strand of inquiry concerned changes in climate. Given the Society's membership, their interest in the glacial epochs that had given Scandinavia its specific geology is not surprising. In 1893, Nils Ekholm gave a lecture on the "astronomical, physical, and meteorological" conditions that could have brought about the Ice Ages following the period of milder climate in tertiary times. The lecture gave rise to a lively debate concerning contemporary theories explaining the Ice Ages. James Croll's idea that changes in the earth's orbit, especially its eccentricity, had brought about the Ice Ages did not find favor among the discussants, nor did the opinion that they were due to changes in the position of the poles on the earth's surface. Among the geologists present, Gerard de Geer chose land elevation as an explanation for a drier and harsher climate. Arvid Högbom did not think that such a drastic geological change could have occurred, for, if that was so, the Ice Ages could not have been interrupted by milder periods.

Here the matter rested until Arrhenius gave a lecture in early 1895 in which he linked climatic change to long-term variations in CO_2. This idea had come to him at the end of 1894, probably after he heard Högbom lecture at the Swedish Society of Chemists. He proposed to calculate the changes in CO_2 necessary to bring about periods of both milder (+8°C) and harsher climate (–5°C), i.e., the conditions which reigned before, during and between the Ice Ages. His preliminary calculations showed that the required changes in CO_2 were in the order of 50%. Högbom, who was present, confirmed that those changes could have occurred in geological times. It remained, however, to demonstrate this quantitatively. The construction of the model which enabled him to do so occupied him for most of 1895. Writing to a friend at the end of the year, he found it "unbelievable that so trifling a matter has cost me a full year" (5). But his complaints in letters to other friends about how difficult it was to bring the "carbonic acid matter" to an end showed how arduous a process this had been. We shall now learn what was involved from a conceptual and a practical point of view.



Arrhenius in his Stockholm laboratory 1908.

THE CONCEPTUAL FOUNDATIONS OF THE MODEL

The conceptual basis for Arrhenius' model is set out in the first paragraph of his article in the *Philosophical Magazine*. It concerns the way the atmosphere retains the heat emanating from the ground ("dark rays") in contrast with that emanating from the sun ("light rays") which is let through. In his rapid review of the history of research on this problem he cited three names: Fourier, Pouillet, and Tyndall.

Joseph Fourier (1786–1830) and Claude-Servais-Mathias Pouillet (1790–1868), both French natural philosophers, are rightly cited by Arrhenius as pioneers in the field. They were both concerned with the temperature of the globe. Fourier established the distinction between the light heat (*chaleur lumineuse*) received on the earth from the sun and the dark heat (*chaleur obscure*) reflected back into the atmosphere. He also pointed to the lesser facility with which dark heat passes through the atmosphere, thus bringing about higher temperatures than would otherwise have been the case. In describing this phenomenon, Fourier drew on experiments conducted by Horace-Bénédict de Saussure (1740–1799), professor of natural history in Geneva. De Saussure had constructed an instrument he called a "solar captor" consisting of a box with an interior covered with black cork in which were inserted layers of glass at equidistance. He used his instrument in experiments around Mont Blanc to show that the temperature under the glass was much higher than on the outside, and that it remained the same irrespective of the altitude (6). In his treatise on the temperature of the globe and the planets, Fourier established the analogy between the heat-conserving capacity of de Saussure's instrument and that of the atmosphere (7). Pouillet used this principle when he worked out the first equation for the thermal equilibrium of "light" and "dark" rays (8). However, none of these three scientists likened heat conservation by the atmosphere to that occurring in a hotbed, hothouse or greenhouse.

Some time during the first three-quarters of the 19th century, someone turned the analogy established by Fourier into the metaphor of the hothouse or hotbed, later to become the greenhouse and attributed it to him (9). The introduction of this metaphor may not have been recorded in a publication, in any event, no such early reference has been found; instead, it became part of the lore passed down from one generation of scientists to another. In his 1888 memoir on the temperature of the moon, Langley took this version for granted, referring to de Saussure's having carried out his experiments "by the use of glass in a hotbed" (10). Since Arrhenius too used this latter term ("drivbänk" in Swedish) (11), it is likely that he took Langley's version for a fact. The article in the *Philosophical Magazine* contained the same version though by then the "hotbed" had become the "hothouse."

Not surprisingly for a physicist, Langley was more punctilious about the correctness of the greenhouse metaphor from a physics point of view than he was with its antecedents. "On the faith of these two eminent names [Fourier and Pouillet]," he wrote, the notion that the processes whereby heat is trapped by the atmosphere are the same as those occurring in a greenhouse, "has been received as a physical datum...where one well-conducted experiment ... would have shown that the action of the terrestrial atmosphere was directly the reverse of that of the glass in a hotbed" (10). The experiment called for by Langley was carried out by R.W. Wood in 1907. It showed that glasshouses retain heat through an absence of convection and advection rather than through the absorption and re-emission of long-wave radiation (12).

Neither Fourier nor Pouillet had discussed the reasons for the heat-absorbing capacity of the atmosphere except in the most general terms. To point to the role of CO_2 and aqueous vapor (H_2O) was the contribution of the British natural philosopher John Tyndall (1820–1893). To Arrhenius it was thanks to Tyndall that one had come to recognize "the enormous importance" of "the influence of the absorption of the atmosphere upon the climate" (13). In support of this statement he cites Tyndall's best-selling book *Heat a Mode of Motion* based on Tyndall's lectures and demonstrations at the Royal Institution (14). Through ingeniously designed experiments and under strict laboratory conditions, Tyndall had measured the heat absorption by gases, among them CO_2 and H_2O. What caught Arrhenius's attention, however, was the discourse "On radiation through the earth's atmosphere." In this short piece, Tyndall assigned to the "atoms" of aqueous vapor a capacity 15 times as large as those of oxygen and nitrogen to retain the heat reflected from the earth, despite the fact that these "atoms" only constitute 0.5% of the atmosphere. Tyndall also made the link with climate by pointing to field observations, made among other places in the Himalayas, which showed how an absence of aqueous vapor caused enormous differences in temperature at different times of the day.

It is noteworthy that Arrhenius does not cite Tyndall's Bakerian lecture in which he is much more explicit about the effect of H_2O and CO_2 on climate. Given Arrhenius's interest in explaining long-term variations in climate it may have been because he did not know about it. Tyndall started his lecture with a reference to the "observations and speculations of de Saussure, Fourier, M. Pouillet, and Mr Hopkins, on the transmission of solar and terrestrial heat through the earth's atmosphere." After having presented his laboratory experiments on the heat-absorption by the gases and vapors of a large number of elements and compounds, he extended these to climate. He noted that "if, as the above experiments indicate, the chief influence be exercised by the aqueous vapor, every variation of this constituent must produce a change of climate. Similar remarks would apply to the carbonic acid diffused through the air, while an almost inappreciable admixture of any of the hydrocarbon vapors would produce great effects on the terrestrial rays and produce corresponding changes of climate. It is, therefore, not necessary to assume alterations in the density and height of the atmosphere to account for different amounts of heat being preserved to the earth at different times; a slight change in its variable constituents would suffice for this. Such changes in fact may have produced all the mutations of climate which the researches of geologists reveal. However this may be, the facts above cited remain; they constitute true causes, the *extent* alone of the operation remaining doubtful" (15).

THE EMPIRICAL BASIS OF THE MODEL

Arrhenius' research question was: What precisely is this *extent* of the influence of H_2O and CO_2 in the atmosphere on the temperature on the ground? Although in the next 30 years, Tyndall's laboratory measurements were extended and supplemented by direct observations by Knut Ångström, Ernst Lecher, Josef Maria Perntner, and Wilhelm Röntgen among others, the question remained unanswered. As Arrhenius pointed out, it would be necessary to carry out a laboratory experiment in which one measured the absorption of the heat emanating from a body at +15°C (the average temperature of the earth) by quantities of H_2O and CO_2 in the proportions in which these were present in the atmosphere, but contemporary research technology did not allow for such an experiment. Instead, he looked for already existing data which he found in Langley's measurements of heat emission in the lunar spectrum. These data became the empirical basis for the model. Without them there is no doubt that his investigation would have foundered.

Samuel P. Langley (1834–1906), an American astronomer and physicist, specialist on infrared spectroscopy, had carried out extensive observations concerning the amount of heat received on the earth from the full moon at the Allegheny Observatory during the years 1885 to 1887 (16). For this he used the bolometer, an instrument he had developed to measure the energy of radiation as a function of wavelength. The bolometer was particularly well suited to measure the small quantities of "dark heat" emitted by the moon that fell in the extreme infrared part of the spectrum. Since the temperature of the moon is similar to that of the earth, their emission spectra would also be similar. Thus, Arrhenius felt confident about using Langley's data. A further simplification was introduced by assuming that the absorption of H_2O and CO_2 by the heat rays entering the earth from the moon when they traversed the atmosphere was similar to that of the heat radiated from the earth into the atmosphere.

The key to Arrhenius' model was the absorption coefficients for CO_2 (designated K) and H_2O (W) that he calculated using Langley's data on the radiation of rays from the moon hitting the earth at angles of deviation ranging from 35° to 40°. He based these calculations on the principle that the quantities of CO_2 and H_2O are proportional to the path of the ray which traverses them (termed "air mass" by Langley). Setting K and W at the value of 1 for a vertical ray, he could calculate how they increased at different angles of deviation; i.e. larger quantities of "air mass". He worked the absorption coefficients into an equation (3) that related changes in K and W to changes in temperature. The equation also took into account the influence of clouds and the heat-moderating effects of snow and water. Working "backwards" as it were, this enabled him to calculate the variations in temperature that would accompany a given change in K and W. Presented schematically, the work of assembling the model thus came to represent a three-stage process. Such a presentation, of course, masks the Herculean labors that his work entailed, involving calculations estimated to have been between 10 000 and 100 000.

The three steps were as follows:

i. A first step involved working his calculations of mean temperatures at different places around the earth into the equation in order to arrive at the temperature change that would follow from a variation from K = 1 to, e.g., K = 1.5. At this stage W was kept constant. Using available charts he calculated mean temperatures during four seasons for every sector situated between two parallels differing by 10° and two meridians differing by 20°.

ii. An intermediary step took into account the fact that the water vapor in the air increases with temperature. Hence, the change in temperature that would follow from the change in K would also influence humidity. To account for this he calculated relative and absolute humidity in the same manner as that for temperature. He found that the influence of humidity on temperature was relatively uniform around the globe.

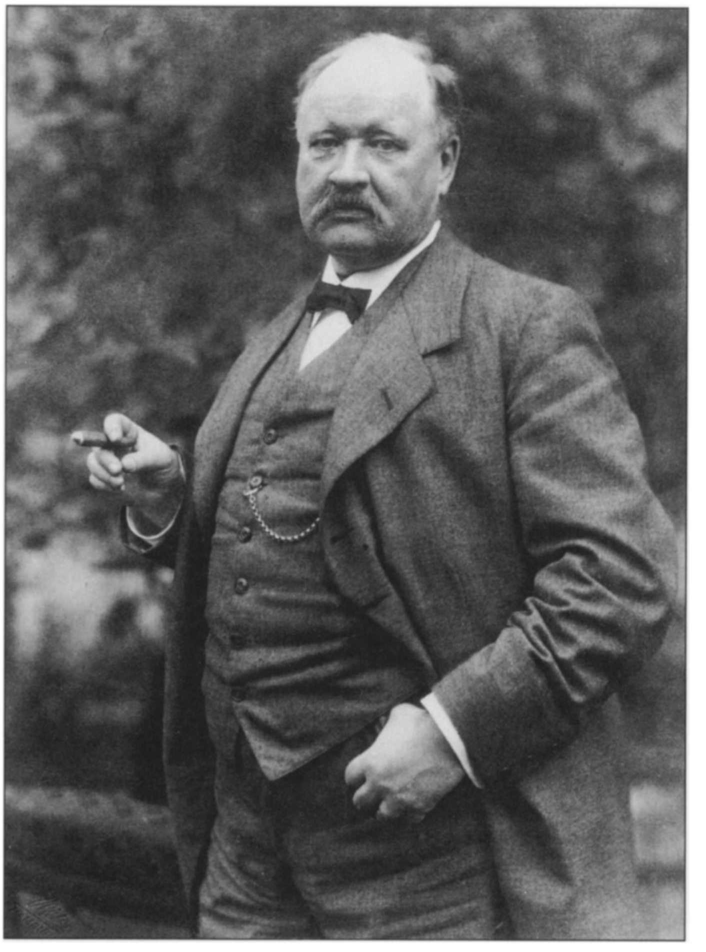
iii. A final step involved the presentation of his data in a table (Table VII) which showed variations in mean temperature in sectors from 70°N to 60°S during four different seasons, assuming that K was respectively 0.67, 1.5, 2.0, 2.5 and 3 times the present observed atmospheric level, that is 1.

The general rule which emerged from the table was that if the quantity of CO_2 increases in geometric progression, temperature will increase nearly in arithmetic progression. For example, if the quantity of CO_2 increases 1.5 times the mean increase in temperature (+3°C) would be the same as the mean fall in temperature (–3°C) brought about by a decrease in CO_2

from 1 to 0.67. The table showed that the effect would be different for different parts of the globe depending on the amount of CO_2 in the air. Thus, in the 0.67 scenario the maximum effect would be on 40° and 50°N whereas in the 3.0 one, they would be north of the 70th parallel. Furthermore, the table indicated that the influence was greater in the summer than in the winter. An increase in CO_2 would also diminish temperature differences between day and night, but this was not shown in the table.

Arrhenius' final results are impressive both as an innovative exercise in model-building and as a first approximation of the influence of CO_2 on climate. This should not make one forget, however, that they hardly rested on solid empirical ground. Arrhenius did not heed Langley's warning that his investigation had yielded "no conclusion which we are absolutely sure of." But Langley's data were the only data available to him. Later, both Langley's data and the use that Arrhenius had made of them were the subject of severe criticisms by Knut Ångström, associate professor in physics at Uppsala University and an expert on measurements of the solar spectrum (17, 18).

Furthermore, Langley's data only allowed for calculations by interpolation of the temperature effects of the 0.67 and 1.5 levels of CO_2 in Arrhenius's table. The three levels above 1.5 were extrapolated as were those below 0.67. The latter (0.62–0.55) giving a temperature decrease of 4–5°C were used by Arrhenius in discussions, both in the article in the *Philosophical Magazine* and in the Physics Society, to argue that an Ice Age brought about by a change in CO_2 was entirely plausible. Conversely, he argued that the doubling and even the tripling of CO_2 showed that periods of warmer climate (increases of 8 to 9°C) had preceded the Ice Ages. Why then were the figures relating to the higher, but not to the lower levels of CO_2, featured in the table? We do not know the reasons for this but we can surmise that it has reinforced the impression that Arrhenius was primarily concerned with global warming not global cooling.



Portrait of Arrhenius.

IMMEDIATE AND LONG-TERM REACTIONS TO THE MODEL

Arrhenius had been inspired to undertake what he referred to as "these tedious calculations" by the debates in the Physics Society concerning the causes of the Ice Ages. It was normal then that the first results should be presented at Society meetings. On two occasions, in May and October 1895, he gave lectures in which he kept the members informed about the progress of his work and reiterated his thesis about variations in CO_2 as a cause of climatic change and especially of the Ice Ages. His model not only provided him with evidence in favor of this thesis, but also with ammunition against competing theories. He took particular pleasure in being able to refute Croll's argument that the Ice ages had been caused by changes in the earth's orbit. Here, he could point to his model to show that Croll's theory, which demanded a clement age on the Southern Hemisphere at the same time as an Ice Age on the Northern Hemisphere, and vice versa, was wholly untenable.

He seems to have had more difficulty in convincing members of the society that he was right in assigning such an important role to changes in CO_2. Even in the discussion in May 1895 Högbom, who had earlier supported the idea of CO_2 as the cause of geological climatic change now sided with those who thought this cause lay in changes in the position of the poles on the earth's surface. After one or two more discussions, equally inconclusive, the Society turned its attention to other questions. This was normal given that the Society was a forum for debate not sustained research. Still, it had played an invaluable role in stimulating Arrhenius' work.

Both local and cosmopolitan publics were important to Arrhenius in making his ideas known. In 1895 and 1896, he took his idea of CO_2-induced climatic change beyond the Physics Society and outside Sweden. In September 1895, he gave a lecture on his work to the Versammlung Deutscher Naturforscher und Ärtzte, best known as the Naturforscherversammlung, whose annual meetings, running the gamut of scientific disciplines, were important gathering places for German and foreign scientists. The 1895 meeting, held in Lübeck, is best known in physics for the epic confrontation that took place between the "energeticists" led by Wilhelm Ostwald and the "kineticists" led by Ludwig Boltzmann, a battle decisively won by the latter. Another occasion to make his ideas known was a popular lecture that he gave at the Stockholm Högskola in February 1896 and published in the Swedish cultural review *Nordisk tidskrift* (11). He reached his largest international audience though, through the article he wrote for the *Philosophical Magazine*. Here he seems to have been motivated chiefly by his desire to refute Croll's hypothesis, which, as he wrote, "still seems to enjoy a certain favor with English geologists" (19).

The only recorded immediate reaction to Arrhenius's article, which came from Thomas Chamberlin, an American geologist at the University of Chicago, concerned CO_2 as the cause of the Ice Ages. In an article published in the *Journal of Geology* in 1897, Chamberlin recounted that he had had the same idea but had not wanted to express in publicly. Arrhenius' and Högbom's work had convinced him that *in a general sense* small changes in CO_2 were quantitatively sufficient to bring about geological climatic change (20). However, when he returned to the topic in an article in the same journal in 1899, he pointed out that Arrhenius and Högbom had failed "to definitely postulate operative geological agencies competent to produce the requisite variations in the constitution of the atmosphere, and to give reasons for believing that such agencies were in operation at the times requisite to produce the effects assigned to them" (21). He also pointed out that Högbom had only considered the different mechanisms that may have caused changes in CO_2, but had not suggested how these could be measured quantitatively.

Chamberlin's criticism was astute but his suggestion was hardly realistic, for at the time it was not possible to obtain such measurements through direct observation. This was evident in Chamberlin's own work, also limited to mechanisms rather than measurements. The only source of CO_2 supplied to the atmosphere that could be measured was in fact that provided by the burning of fossil fuels. In his article, Högbom had pointed out that the CO_2 produced by the 500 million tons of coal annually burnt by modern industry represented about a 1000th part of CO_2 in the atmosphere (4). He found, however, that this quantity was offset by the CO_2 consumed in the formation of limestone through weathering.

In his popular lecture at the Högskola, Arrhenius went a step further and ventured a prediction of how long it would take for fossil-fuel burning alone to double the amount of CO_2 in the atmosphere. In an addendum to the published lecture he presented calculations of the buffering effects of the oceans, which Högbom had considered but had not quantified. These showed that if six parts of CO_2 are added to the atmosphere, five will be absorbed by the oceans. In view of this, a doubling of CO_2 that would have taken 3000 years if the earth was a single land-mass would occur in 500 years. During this latter period, temperatures would increase by 3–4°C. Arrhenius saw nothing adverse in such a development. It will "allow our descendants," he said, "even if they only be those of a distant future, to live under a warmer sky and in a less harsh environment than we were granted"(11). Such a view is consonant with the ideology of "optimistic evolutionism" embraced by Arrhenius and many of his contemporaries (22).

Arrhenius's references to coal burning as a source of atmospheric CO_2, repeated and revised upwards (but without the predictions he ventured in his Högskola lecture) in his *Lehrbuch der kosmischen Physik* (1903) (23), and *Worlds in the Making* (1908) (24), are probably what has earned him his present reputation as the first to have predicted the effect of this particular source of CO_2 on climate. This view overlooks the fact that fossil-fuel burning by industry figured in Högbom's geological carbon cycle and the equally important fact that Arrhenius gave Högbom credit for this. This neglect forms part of course of the general way that Högbom's contribution has been forgotten.

The image of Arrhenius as the "discoverer" of the greenhouse effect would not have taken hold without the recontextualization that occurs when a scientific problem is taken out of its historical context and placed in one that reflects present-day concerns. It is thus that interest in Arrhenius's model, which had been minimal during the first 50 years of the 20th century, was resuscitated in the 1970s as a result of the model being placed in the new context of global warming. As often happens, the recontextualization of a work has led to its reinterpretation. In Arrhenius's case, this has been important in two ways: first, with respect to the meaning of the "greenhouse effect," which to him was simply the warming effect of atmospheric gases which are radiatively active and *not* the anthropomorphic influence on the production of such gases, and, second, with respect to his motives for undertaking the work, which were an interest in finding the causes of the Ice Ages and *not* concern with the effect of the industrial revolution.

CONCLUSION

The genesis of Arrhenius' work was in the tradition of glacial climatic change, represented by Tyndall, Croll and Chamberlin, among others. In important respects, however, his work broke with this tradition. This break did not lie so much in the part of his work which is most often cited today, i.e., the link he made between industry's burning of fossil fuels and global warming. This link may have been largely fortuitous in that it depended on the paucity of data concerning other sources of atmospheric CO_2. Two other features of his work were much more remarkable: one was linking Högbom's work on the carbon cycle to climatic change—Högbom's work being in itself a major achievement for which he has only very recently received renewed credit (25)—and the other was constructing a model which for the first time made possible predictions of both global warming *and* cooling.

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