ourselves with respect to the greenhouse effect and its potential repercussions on future generations.

In our view, the NRC panel seriously underestimates the research effort required to reduce the uncertainty in aerosol forcing to the specified level. The task of characterizing tropospheric aerosols, their spatial and temporal variability, their size-dependent chemical and physical properties, and their optical and cloud-nucleating effects; of understanding the processes controlling these properties and effects; of representing these processes in models; of evaluating the performance of these models; and of representing these effects in climate models requires a research effort several-fold greater than that outlined in the report. In the absence of this research, knowledge of climate response to greenhouse forcing necessary for confident policymaking will be reliant entirely on climate models having little credible empirical confirmation.

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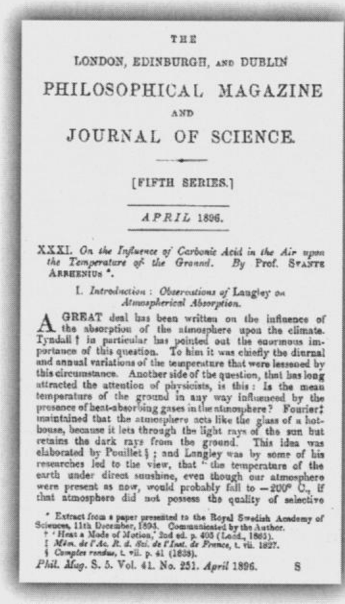
Arrhenius and Global Warming

Although concern about global atmospheric warming has intensified in recent decades, research into the greenhouse effect actually began in the 19th century. Fourier compared the influence of the atmosphere on temperature to the heating of a glass-covered bowl with an interior coated with black cork (*1*). He and other scientists such as Tyndall (*2*) and Langley (*3*) appreciated that without heat-absorbing gases in the atmosphere, the temperature on the ground would be considerably lower, making life as we know it impossible. However, in 1896 the Swedish scientist Svante Arrhenius was the first to make a quantitative link between changes in CO_2 concentration and climate (*4*). The centenary of the publication of his paper was celebrated at a recent workshop at the Royal Swedish Academy of Sciences (*5*).

Although he had a wide range of interests, Arrhenius is best known for his work on electrolytic dissociation, for which he received the Nobel prize in Chemistry in 1903, and on the theory of reaction kinetics. In his work on the effect of CO_2 on global climate (*4*), Arrhenius made clever use of data provided by Langley (*6*), who had measured the emission spectrum of the moon for different lunar heights and seasons. This data allowed the calculation of the absorption coefficients of CO_2 and H_2O and of the total heat absorbed in the atmosphere of the Earth for a variety of CO_2 concentrations, as well as the corresponding temperature change.



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XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.* By Prof. SVANTE ARRHENIUS *.

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 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 ‡ 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 §; 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

* Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December, 1895. Communicated by the Author.
† 'Heat a Mode of Motion,' 2nd ed. p. 405 (Lond., 1865).
‡ *Mém. de l'Ac. R. d. Sci. de l'Inst. de France*, t. vii. 1827.
§ *Comptes rendus*, t. vii. p. 41 (1838).

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Hot paper. Title page of Arrhenius's paper in *Philosophical Magazine.*

After an estimated 10,000 to 100,000 calculations by hand (*7*), Arrhenius predicted a temperature rise of 5° to 6°C for a doubling of CO_2, not too different from recent estimates of 1.5° to 4.5°C (*8*). Arrhenius primarily ascribed changes in CO_2 levels to changes in volcanic activity and concluded that they could be the cause of glacial cycles on a geological time scale. In a lecture in 1896 (*9*), he estimated that a doubling of CO_2 as a result of fossil fuel burning would take 3000 years. At the time, he was rather in favor of the resulting slow warming, which in his view would result in better living conditions and higher crop yields.

Arrhenius's work, and that of his contemporaries, showed remarkable insight into many factors influencing climate, such as aerosols, ice fields, clouds, and the oceans as a sink for CO_2. In the 1930s, human forcing of climate through fossil fuel emissions began to be considered as a cause of significant temperature increases in the short term (*10*). Today, sophisticated atmospheric models (general circulation models) incorporate a growing number of factors (*11*). Compared to the real climate, these models are still crude: typical parameters are a time step of 1 hour, a spatial grid size of 250 km, and up to 20 vertical levels (*12*). Reliable long-term observational data of climate system variables and detailed physical understanding of feedback mechanisms associated with, for example, clouds, oceans, and vegetation are often lacking. However, there is general agreement among many different studies about the detection of change and its attribution to natural or human-induced influences.

Last year, the Intergovernmental Panel on Climate Change (IPCC) concluded that "the balance of evidence suggests that there is a discernible human influence on climate" (*13*). Despite uncertainties in climate predictions and a highly political climate, perhaps it is reassuring that 100 years of research have affirmed Arrhenius's initial considerations.

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