Part One

The early history of the climate change issue

1

Nineteenth-century discoveries

Variations of atmospheric concentrations of carbon dioxide may well change the global climate.

The nineteenth century saw a remarkable development of our knowledge about past climatic variation. The French natural philosopher Joseph Fourier (1824) put forward the idea that the climate on earth was determined by the heat balance between incoming solar radiation ('light heat') and outgoing radiation ('dark heat') and this idea was further pursued by Claude Pouillet (1837). They both realised that the atmosphere might serve as an absorbing layer for the outgoing radiation to space and that the temperature at the earth's surface might therefore be significantly higher than would otherwise be the case.

At about the same time the Swiss 'naturalist', Louis Agassiz (1840) suggested that features in the countryside, such as misplaced boulders, grooved and polished rocks, etc., were indications of glacial movements and that major parts of central Europe, perhaps even northerly latitudes in general, had been glaciated. This revolutionary idea was, of course, not readily accepted by his colleagues, but it stimulated others to search for further evidence. Agassiz's idea found acceptance during the following decades, not least because of his studies in the Great Lakes area in the USA.

The idea that the atmosphere plays an important role in determining the prevailing climate of the earth was further developed in England by John Tyndall (1865). He actually measured the heat absorption of gases, including carbon dioxide and water vapour, and emphasised their importance for the maintenance of the prevailing climate on earth. He thought that variations of their concentrations might explain a significant part of the climate variations in the past. Thus Tyndall clarified qualitatively what we today call the *greenhouse effect*, but he did not attempt to quantify its role. Data were simply inadequate to do so.

Agassiz's discoveries and work by other researchers in central Europe also attracted geologists in Scandinavia, particularly Gerhard De Geer in Sweden, who contributed greatly to the advance of our knowledge of glaciations over Scandinavia. De Geer studied the layers of clay that can be found in lakes and in areas earlier submerged by lakes or by the sea at the time of the decline of the major ice sheet over Scandinavia. He was able to show that the layers represent annual deposits of particles that were set free in the course of melting and carried by the runoff of the melt water to less turbulent places where deposition could occur. He was able to use his extensive data set to determine accurately the chronology of the withdrawal of the Scandinavian ice sheet.

The natural questions to ask were of course: Why did the climate become warmer some 10 000 years ago? How long had there been an ice age? Obviously the heat balance between the earth and space must have been disturbed in some way. It was already known at that time that the elipticity of the earth's orbit around the sun varies regularly, which creates a periodic variation of the incoming solar radiation and its distribution over the earth. James Croll in England considered such variations as the most likely reason for the observed variations of climate. Alternatively, the optical characteristics of the atmosphere or the earth's surface might have changed, but why?

This was the state of knowledge in the early 1890s when a group of scientists at Stockholm's Högskola[1] addressed the issue anew under the leadership of Svante Arrhenius.[2] He had recently been appointed teacher of physics at the Högskola and was keen for his research to be of relevance to society. He had put the physics of our environment in the broad sense of the word high on his agenda. To some extent this was a protest against the traditional role of many universities in the late nineteenth century, particularly the University of Uppsala as Arrhenius had experienced himself. He had had great difficulty in having his doctor's thesis approved at Uppsala some ten years earlier, but since then had gained international recognition for his development of the theory of the dissociation of solutions. The relations between the faculties in Stockholm and Uppsala remained tense.[3]

Under Arrhenius' leadership some remarkable discussions and analyses were initiated. As one of his first actions as professor at Stockholm's Högskola he founded the Stockholm Physics Society. The members met every other Saturday morning for a public seminar. Lectures were given and the discussions were open and lively. The group included: Vilhelm Bjerknes, professor of theoretical physics, later renowned for his development of physical hydrodynamics, who thus provided a solid foundation for modern meteorology; Otto Petterson, oceanographer; Arvid Högbom, geologist and one of the first to analyse the circulation of carbon in nature; and Nils Ekholm from the Swedish Meteorological Office, a specialist in atmospheric radiation.

Arrhenius' decision in 1894 to study the mechanisms of climate change was probably a result of a presentation by Ekholm of Croll's idea that climate variations were primarily caused by variations of solar radiation and another one by Högbom describing sources and sinks for the carbon dioxide in the atmosphere, both given as Saturday seminars. Arrhenius wanted to determine the sensitivity of the climate system to changes of the water vapour and carbon dioxide concentrations in the atmosphere. He was intuitively sceptical of Croll's view about the importance of variations of solar radiation and was curious about the magnitude of possible variations of the greenhouse effect due to changes in the concentrations of water vapour and carbon dioxide in the atmosphere. However, this required knowledge of their radiative characteristics. Adequate laboratory measurements were not available, but the American physicist Langley (1889) had deduced the temperature of the moon by observing its dark (infrared) emissions. Arrhenius realised that these data could also be used to determine quantitatively the absorption by the atmosphere due to the presence of these heat-absorbing gases by evaluating the intensity of their absorption as a function of the angle of elevation of the moon.

Arrhenius also recognised early that there is a most important feedback mechanism that must be considered. If the air becomes warmer because of an increasing carbon dioxide concentration, it is likely that the amount of water vapour in the atmosphere will also increase because of enhanced evaporation. This would in turn cause additional warming. Conversely, cooling would be enhanced if the carbon dioxide concentration were to decrease. In fact, the plausible assumption made by Arrhenius that the relative humidity probably would remain unchanged yields an enhancement of the warming due to an increase of the carbon dioxide concentration of at least 50%. It is interesting to note in passing that the magnitude of this feedback mechanism was a controversial issue until the 1990s. Let us recall Svante Arrhenius' own description of the greenhouse effect as given in a popular lecture early in 1896:[4]

> As early as at the beginning of this century, the great French physicists Fourier and Pouillet had established a theory according to which the atmosphere acts extremely favourably for raising the temperature of the earth's surface. They suggested that the atmosphere functioned like the glass in the frame of a hotbed. Let us suppose that this glass has the property of transmitting the sun's rays so that objects under the glass are warmed, but not of transmitting the heat radiation emitted by the object under the glass. The glass would then act as a sort of trap which lets in the heat of the sun but does not let it out again, when it has been transformed to the radiation of bodies with a lower temperature. Glass does in fact act in this way, as has been shown by experiments, although only partially, not totally, so. According to Fourier and Pouillet a similar role is played by the earth's atmosphere which, one might say, retains the sun's heat for the earth's surface. The more transparent the air becomes for the sun's rays, and the less it

becomes so for the heat radiation from the earth's surface, the better it is for the temperature of the earth's surface.

The transparency of the air depends principally on three factors. Extremely fine suspended particles in the air impede the penetration of the sun's heat, although they have little effect on the heat radiated by the earth. Further, the clouds reflect a great deal of the sun's heat which impinges on them. The main components of the air, oxygen and nitrogen, do not absorb heat to any appreciable extent, however, the opposite is true to a high degree for aqueous vapour and carbonic acid in the air, although they are present in very small quantities. And these substances have the peculiarity that to a great extent they absorb the heat radiated by the earth's surface, while they have little effect on the incoming heat from the sun.

It should be pointed out, however, that the analogy of the hotbed (or, as we say today, greenhouse) is deficient in one important way. The glass has an additional function in a greenhouse in that it prevents the hot air beneath it escaping. The atmosphere, on the other hand, is often mixed by convective currents, whereby heat is transferred to higher levels, from where radiation to space takes place. The term greenhouse effect has, however, come to stay, since it describes an important mechanism simply, though not perfectly.

Arrhenius spent most of 1895 carrying out the very tedious computations that were required to give a quantitative answer to the question he had asked. He kept the members of the Physics Society informed by giving two presentations in the course of the year. In 1896 his paper on this work was published by the Royal Swedish Academy (in German) and the *Philosophical Magazine* in England (Arrhenius, 1896a).

Arrhenius presented the expected change of the surface temperature as a function of latitude and time of the year for carbon dioxide concentrations equal to 0.67, 1.5, 2.0, 2.5, and 3.0 times the prevailing concentrations, which were assumed to be about 300 parts per million of volume (ppmv). He thus explored the consequences of both a decrease and an increase of carbon dioxide concentrations. The spatial and temporal distributions that he determined are of secondary interest, since in reality the motion of the air would change these distributions, but he determined that the average global change of surface temperature due to a doubling of the carbon dioxide concentration would be 5.7 °C. He recognised that the precise magnitude of the warming is uncertain and he later reduced this figure somewhat on the basis of additional computations.

Arrhenius drew the conclusion that variations of the amount of carbon dioxide in the atmosphere might well be an important factor in explaining climate variations thereby refuting Croll's hypothesis. He referred to the view expressed by Högbom that volcanic eruptions add carbon dioxide to the atmosphere, but there were no data to support his view that this might have been the reason for the ending of the last ice age.

Arrhenius also explored the possibility that human emissions of carbon dioxide might bring about a global warming. The annual emissions due to coal burning at that time were about 400 million tons of carbon, i.e. 0.7 per thousand of the amount present in the atmosphere. He believed that a significant part of these emissions must, however, be removed by the dissolution of carbon dioxide in the sea. He rightly pointed out that at equilibrium only about 15% would stay in the atmosphere but did not realise that the turnover of the sea is a slow process and that it actually takes more than a millennium to reach equilibrium. We know today that only about 20% of the emissions to the atmosphere since the beginning of the industrial revolution some 150 years ago have dissolved in the sea. However, Arrhenius did not know that the use of fossil fuels would increase very rapidly, in fact by a factor of about 15 during the twentieth century. He therefore dismissed the possibility that man one day might cause significant global warming, but would have welcomed such a development. He actually wrote (Arrhenius 1896a): 'It would allow our descendants, even if they only be those in a distant future, to live under a warmer sky and in a less harsh environment than we were granted.'

Arrhenius' evaluation of the greenhouse effect is a remarkable achievement. This is brought home by two leading researchers in the field today, Ramanathan and Vogelmann (1997), who characterise his work as follows:

> Svante Arrhenius laid the foundation for the modern theory of the greenhouse effect and climate change. The paper is required reading for anyone attempting to model the greenhouse effect of the atmosphere and estimate the resulting temperature change. Arrhenius demonstrates how to build a radiation and energy balance model direct from observations. He was fortunate to have access to Langley's data, which are some of the best radiometric observations ever undertaken from the surface. The successes of Arrhenius model are many, even when judged by modern day data and computer simulations.

Arrhenius' analysis of the climate change issue was discussed for a few years, but there were not enough data to tell whether he was right or wrong. The amount of carbon dioxide could not be measured with sufficient accuracy to determine if it actually was increasing. We can today assess that the annual change then would have been less than 0.1 ppmv, which was much less than could be measured at that time. Still, his fundamental scientific work led to a much deeper understanding of key environmental processes.

Almost 100 years were to pass before Arrhenius' findings became of political interest. His discovery was a very early one and it illustrates well the fact that fundamental research often uncovers surprises that can be either destructive or beneficial. It is obvious that there was as yet no societal concern that the further development of an industrial society might lead to the impoverishment of the natural world around us. The concept of the environment as an asset beyond its provision of natural resources had not yet been recognised. Scientists, politicians and industrialists had no reason to worry about issues of this kind and the twentieth century began with an optimistic attitude towards the future.

Throughout the twentieth century, experts have been familiar with Arrhenius' work, but it was largely regarded as being something that might have to be looked at again more closely in the future. It was not until 1957 that Keeling (1958) was able to develop an accurate method of measuring the amount of carbon dioxide in the atmosphere and could show that the annual rate of increase at that time was about 0.6 ppmv and that this increase was probably due to human emissions caused by burning fossil fuels. At about the same time a renewed interest in learning about the biogeochemical cycle of carbon and climate change also emerged.

2

The natural carbon cycle and life on earth

Our knowledge about the global carbon cycle can be made more robust by making use of the condition of mass continuity, distributions of tracers and interactions with the the nutrient cycles.

2.1 Glimpses of the historical development of our knowledge

Carbon is the basic element of life. All organic compounds in nature contain carbon and the carbon dioxide in the atmosphere is the source of the carbon that plants assimilate in the process of photosynthesis. An understanding of the global carbon cycle is of basic importance in studies of human-induced climate change, not only because of the need to determine expected changes of atmospheric carbon dioxide concentrations due to human emission, but because natural changes of the carbon cycle may also have influenced the climate in the past.

The detection of the fundamental chemical and biochemical processes of relevance in this context is a most important part of the development of chemistry during the eighteenth century and the first decades of the nineteenth century. Joseph Black (1754) is credited with the discovery of carbon dioxide gas. Its real nature was, however, not very well understood until Carl W. Scheele in Sweden and Joseph Priestley in England identified ‘fire air’ (i.e. oxygen) a few decades later and the French chemist Lavoisier correctly interpreted the concepts of fire and combustion. When carbon burns, carbon dioxide is formed.[1]

It was not realised until well into the nineteenth century that carbon dioxide, like oxygen and nitrogen, is a permanent constituent of the air and that it is a source of carbon for plants. However, it was not then possible to measure the amount present in the atmosphere. In fact, it was not until the end of the century that the average atmospheric concentration of carbon dioxide was determined to be somewhat less than 300 ppmv. The analytical techniques were reasonably accurate, but it was not fully realised that the local carbon dioxide concentration in the air varies markedly due to its role in biological processes and also because of emissions from burning coal (From and Keeling, 1986).

When Arrhenius published his major paper on the role of carbon dioxide in the heat balance of the earth (Arrhenius, 1896a), it was not known whether or not the atmospheric concentration might be rising as a result of the increasing use of coal. Even though Arrhenius dismissed the possibility that man could influence the atmospheric concentration significantly in that way, the possibility remained in the back of the minds of several researchers during the first half of the twentieth century.[2] One may quote Lotka, who was the father of 'physical biology.' He became interested in the carbon cycle when developing this new concept. In 1924 he wrote very optimistically:

> . . . to us, the human race in the twentieth century, this phenomenon of slow formation of fossil fuels is of altogether transcendent importance: The great industrial era is founded upon the exploitation of the fossil fuel accumulation in past geological ages . . . We have every reason to be optimistic, to believe that we shall be found, ultimately, to have taken at the flood of this great tide in the affairs of men; and that we shall presently be carried on the crest of the wave into a safer harbour. There we shall view with even mind the exhaustion of the fuel that took us into port, knowing that practically imperishable resources have in the mean time been unlocked, abundantly sufficient for all our journeys to the end of time.

This he said in spite of the fact that he recognised the complexity of the issue:

> But whatever may be the ultimate course of events, the present is an eminently atypical epoch. Economically we are living on our capital; biologically we are radically changing the complexion of our share in the carbon cycle by throwing into the atmosphere, from coal fires and metallurgical furnaces, ten times as much carbon dioxide as in the natural biological process of breathing. These human agencies alone would . . . double the amount of carbon dioxide in the entire atmosphere . . .

The first decades of the twentieth century saw the beginning of ecological thinking and in this context the circulation of carbon was also brought into focus. Vernadsky in Russia wrote his ground-breaking book on the biosphere in 1926, in which he recognised for the first time what we today call global ecology. He emphasised that '. . . the Earth, its atmosphere as well as its hydrosphere and landscapes, is indebted to living processes, i.e. the biota, for its present composition.'

In 1935 his colleague Kostitzin developed a quantitative model of the carbon cycle and recognised the necessity of considering in this context its interplay with the circulation of oxygen and nitrogen and in particular long-term changes in their abundance in the atmosphere and the soil. This was long before the concept of biogeochemical cycles and their interactions became a generally accepted view of the dynamics of environmental interactions. These researchers were indeed pioneers.

In England Callender (1938) addressed the question of a possible increase in atmospheric carbon dioxide due to burning of fossil fuels. He recognised that the lowest values that had been observed towards the end of the nineteenth century had usually occurred in the middle of the day and when the air was of marine or polar origin. He correctly drew the conclusion that mixing of the air horizontally as well as vertically is most efficient under these circumstances. Atmospheric concentrations were therefore likely to be least influenced by local conditions and accordingly most representative on these occasions. Callendar concluded on the basis of the measurements taken during the last decades of the nineteenth century that the most likely average concentration between 1872 and 1900 was around 290 ppmv with an uncertainty of about ± 10 ppmv.[3]

This value is just slightly above what is deduced from analyses of the carbon dioxide content of air bubbles in glacier ice formed at that time. When air between the snowflakes that are deposited on the ice sheets in Antarctica and Greenland is shut off from direct contact with the atmosphere because of the accumulation of snow in the following years, air samples are created and their carbon dioxide content can be measured. By counting the number of layers that have been formed these samples can also be dated.

In the late 1950s Keeling developed a new method for measuring the amount of carbon dioxide in air and was able to show that the atmospheric concentration had risen to about 315 ppmv in the late 1950s and was increasing annually by about 0.6 ppmv (see Keeling (1960)). This is equivalent to an increase in the amount of atmospheric carbon dioxide of about 1.2 Gt C per year,[4] which corresponds to just about 0.2% of the carbon in atmospheric carbon dioxide at that time (about 670 Gt C). The annual emissions due to fossil fuel burning were, however, about 2.5 Gt. and the annual increase in the atmospheric concentration corresponded thus to merely about 50% of these emissions. The accumulated emissions due to fossil fuel burning since the industrial revolution began were then estimated to have been about 80 Gt C. These simple findings were very important and raised a number of basic questions that were addressed during the next few decades. First, there is obviously a significant exchange of carbon dioxide between the atmosphere and other natural carbon reservoirs, the sea and the terrestrial biosphere, i.e. vegetation and soils, and presumably also a net transfer from the atmosphere into these when the atmospheric concentration increases. Carbonate rocks are by far the largest reservoir of carbon on earth, but one could ask if the rates of weathering, and thus release of carbon from rocks to water and air, were small compared with the human emissions due to fossil fuel burning, and also compared with the natural flux of carbon