Climate science – how did it come about?

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1. Intro

The greenhouse effect and rising global temperatures have been predicted since the late nineteenth century, by which time it was evident that the exponential growth in coal burning was releasing enormous amounts of carbon dioxide into the atmosphere. At that time, however, hardly anybody was interested in the matter. Even 40 years later, when climatologists observed a significant rise in temperatures between 1920 and 1940, climate change was not of interest to scientists, politicians or the general public. It took around another 40 years or more before carbon dioxide emissions began to be considered a threat and started causing concern. Surprisingly, this change of perception occurred at a time when global temperatures had stagnated. So, what made scientists believe in climate change, and why and when? And how come that climate science suddenly became a field of high political priority in the late 1980s, but not in the 1930s? This chapter sets out to provide some answers.

When the famous Swedish physicist Svante Arrhenius predicted rising temperatures due to growing carbon dioxide emissions in 1897, little attention was paid to his result. Four decades later, the engineer Guy Callendar faced similar reservations. Callendar was puzzled by rising carbon dioxide emissions and expected an unavoidable change of climate. Based on meticulous calculations he came up with a prediction of climate warming caused by the greenhouse effect. Well aware of a significant rise in temperature, which had been observed since about 1920 in northern Europe, Callendar was convinced he had the proper explanation. To his surprise, climatologists were not convinced. Climatologists, instead, considered Callendar's theory highly unlikely and preferred an alternative explanation. They believed that accidental and temporary shifts of meteorological circulation systems (shifts of the pathways of high and low pressure systems), which had been experienced in the past, explained the regional and local shifts in temperature (or precipitation). Callendar's theory could only explain global

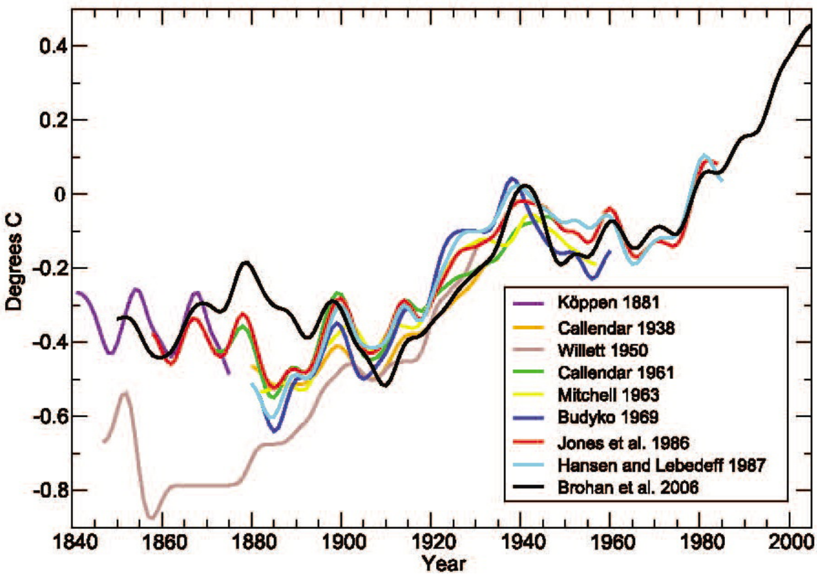


Figure 1: Published records of surface temperature change over large regions. (Source: IPCC-Report 2007, p. 101).

temperature changes, as carbon dioxide emissions uniformly mixed in the atmosphere and caused a greenhouse effect everywhere on earth. Which left the question of why the arctic region should be especially affected by increasing temperatures?

Climatologists appeared to have the empirical evidence on their side. The warming tendency in Europe and in the arctic regions came to a halt in the 1940s. Stagnating temperatures for the next three decades – at a time of strong economic growth and rapidly rising energy use and carbon dioxide emissions – did not provide much proof of climate change. Were Arrhenius and Callendar and their theories mistaken? In 1965, a conference at the newly founded National Center for Atmospheric Research in Boulder, Colorado in the USA showed that scientific perceptions and perspectives had suddenly turned. The conference was entitled “Causes of Climate Change”. Climate change, the scientists now believed, was a real threat, and its causes were believed to be: carbon dioxide and the greenhouse gas theory! This conference represented a turning point after which scientists began to investigate climate change and to communicate its risk to politicians and the public. Obviously, there is no simple relationship between temperature observations and a belief in climate change. So, what had happened between the 1890s and the 1960s? How could the idea of climate change be dismissed for so long despite significant evidence, and then become accepted during a time of stagnating temperatures? Apparently, no simple historical logic framed the emergence of climate change science. Scientific findings certainly played a significant role in the shaping of this field of science, but perhaps equally important were the technological innovations, military and economic interests and social demands that characterised the period.

2. Features of classical climatology

Interest in climate had a long tradition. Greek philosophers like Parmenides, Eratosthenes and Aristotle reflected on climate and its effects. The term "climate" originates from the ancient Greek word "κλινειν" ('klinein'), which means "incline". Climate was directly associated with the inclination of the sun on the earth's surface: the bigger the inclination, the weaker the sunlight and the colder the climate. This, however, was not the full truth, as the Greek philosophers admitted. Features of landscape and weather, oceans and mountains, wind regimes and seasons obviously also played their role.

Systematic research on climate began much later. Alexander von Humboldt is regarded as one of the pioneers in the field. He was the first to clearly outline the prerequisites for a science of climate in the first half of the nineteenth century. Crucial for the emerging field of climatology was Humboldt's definition of climate. Climate meant "in the most general sense all changes in the atmosphere which noticeably affect the human organs", such as temperature, humidity, barometric pressure or wind (Humboldt 1845, Bd. I, p. 340). Humboldt's understanding of climate proved important in three respects. First, climate was always associated with a specific location. Geographical locations had a certain climate and in different places like Copenhagen or Rome the climate differed in specific ways. From Humboldt's perspective the term climate did not make sense without reference to a specific location. Second, the concept of climate was directly linked to the experience of humans. Only those atmospheric phenomena which had an effect on the human senses were regarded as elements of climate by Humboldt. Other atmospheric phenomena (like cosmic radiation or wind velocities at a height of three kilometres or more) did not represent elements of climate, because they had no impact on the human senses. Third, Humboldt formed a holistic concept of climate. Climate could not be reduced to single parameters (like temperature), but involved all atmospheric phenomena affecting the human senses.

Climate was seen as stable over time, but changing from place to place. Humboldt, thus, shaped a geographical understanding of climate. In the second half of the nineteenth century, climatologists like the Austrian Julius von Hann and the Russian Wladimir Köppen adopted Humboldt's conception of climate and made it the basis of a rigorous science. Climatology in their vein was an effort of systematic collection and evaluation of meteorological data and of analysing their broader relationships in order to identify the specificities of local and regional climates. Von Hann invented the foundations of a quantitative description of climates by averaging long-term time series of meteorological data such as temperature, precipitation, etc. from a particular location. His climatology, therefore, was called an "averaging climatology". Köppen followed von Hann's climatology. He collected systematically large amounts of climatologic and geographical data and subsequently brought the climates of the earth into systematic order. In the early twentieth century, Köppen constructed climate maps representing different climate zones on the earth. These climate zones were based on his definition of classes of climate like "tropical climate", "subtropical climate", "polar climate" etc., concepts which still are in use today.

The climatology founded by Hann and Köppen represented the core of what could be called "classical climatology". It defined the standard programme of climatologic research in the first half of the twentieth century. This climatology saw its task as the collection and evaluation of climatologic data in order to produce, complete and refine the quantitative description of the climates on earth and provide proper data bases for the investigation of the effects of local climates on vegetation, agriculture and human health. Subsequent editions of the handbook of climatology, which von Hann first published in 1883, reflected the progress in climatology. The description of climates of specific regions on earth increased from half a volume in 1983 to four full volumes in the 1930s. Classical climatology maintained a conception of climate which emphasized its stability over time and variability with respect to geographical location.

This kind of climatological research formed a backdrop for the physicist Svante Arrhenius in the 1890s and the engineer Guy Callendar in the 1930s to come up with their versions of a greenhouse gas theory based on rising concentrations of carbon dioxide in the atmosphere. At that time, their concepts of climate change did not fit at all well with the contemporary climatologic methodologies and beliefs. Not rooted themselves in the tradition of climatologic research, Arrhenius and Callendar went their own original ways. Climatologists, however, didn't want to follow. Arrhenius' and Callendar's main methodological tool – calculations based on physical laws – was foreign to climatologic methodology. Finally, both Arrhenius and Callendar were not part of the scientific community of climatologists.

Even though they studied climatologic thinking, methodology and language to a considerable extent, they remained foreigners to the community of climatologists. These factors may have contributed to the reluctance with which their theories were received.

3. Technological change and conceptual shift

It remained a long way to go from classical climatology to the climate change science of today, a way which was not paved with logic or linear progress, but owed much to historical coincidence. While classical climatology focused on data collection close to the surface of the earth, von Hann and Köppen also supported the taking of measurements at higher layers in the atmosphere. Such measurements were provided by a few mountain stations and with the help of kites or balloons that transported the instruments to great heights. But the extent of such measurements remained extremely limited throughout the nineteenth century. Climatologic data and, consequently, climatologic knowledge, perceptions and understanding largely extended over the two dimensions of the surface of the earth. In the first half of the twentieth century, this limitation slowly dissolved when a rapid expansion of knowledge about the higher atmosphere occurred – the "discovery", as one could paraphrase it, of the third dimension of the atmosphere. And this discovery enriched meteorological knowledge enormously. Coherent wind regimes at great heights, the so-called jet streams, were discovered, for example.

The "discovery" of the third dimension of the atmosphere had a very practical background. In 1903 the brothers Orville and Wilbur Wright succeeded in making the first powered flight in a small motorized aircraft. At about the same time Count Ferdinand Zeppelin started to construct huge airships. The dream of flying was about to become reality. With the onset of World War I aircrafts and airships exhilarated the public and the military alike. The advances in flying technology had a knock-on effect on meteorology. Aircrafts and airships were highly sensitive devices, and as such strongly dependant on weather. Very soon there was a demand for weather data from the higher atmosphere, and with this demand a new climatologic discipline began to develop, which Köppen in 1906 named "aerology". The war accelerated the course of developments. Flight technology as well as aerology thrived, pushed by military and, after the war, commercial interest. After 1937, and the introduction of radiosondes (which could send measurement results back to earth by radiowaves), there was an explosion of data from the higher atmosphere. While in 1930 weather services provided data from about 3,000 balloon or kite launches a year, this number skyrocketed to about 180,000 twenty years later.

Technological demand combined with military and commercial interest was only one part of a complex combination of events that helped to shape climatologic development. Also, of tremendous importance was the development of dynamical meteorology. Von Hann had made a clear distinction between climatology and meteorology. While climatology was a descriptive and holistic geographical science, which aimed to provide comprehensive descriptions of regional climates, meteorology was a reductionist physical science interested in the mathematical description of meteorological parameters so that predictions about the weather could be made using the laws of physics. At the end of the nineteenth century, geographical climatology had established its methodological foundations, while physical meteorology still struggled to master the complexity of meteorological phenomena. The number and causal relationships between the atmospheric parameters proved difficult to describe mathematically. As a consequence, meteorology was limited to data collection and evaluation without coming any closer to weather prediction based on scientific laws. Scientifically-minded meteorologists suffered from failure and disregard, while meteorology was not even considered a science by many physicists.

In 1903, the Norwegian physicist Vilhelm Bjerknes described a new framework for dynamical meteorology. Bjerknes sought to make meteorology a true physical science able to calculate and predict the weather. He claimed that all meteorological processes in the atmosphere could be described by seven parameters and six differential equations describing the mathematical relation of these parameters. In principle, what Bjerknes' scheme achieved was a complete description of the physical processes in the atmosphere. But solution of these highly non-linear differential equations proved impossible. Bjerknes and his group of students at the University of Bergen, the so-called Bergen school of meteorology, developed graphical methods that could be used to gain approximate solutions of the differential equations. But, weather prediction still proved impossible because much more data on the current state of the atmosphere was needed in order to predict future states.

Not long after, the British scientist Lewis Fry Richardson approached the same problem using a very different strategy. Richardson attempted an approximate so-called numerical solution of the differential equations. Though this strategy was feasible, it proved far too laborious and time-consuming. Richardson engaged in the cumbersome calculations for a period of many months before being able to predict the weather for one single day at two locations. Such long calculation times meant meaningful predictions were impossible, because the weather being predicted would have been and gone by the time the result was achieved. If such predictions were to be of use, they would have to be carried out within few hours. According to Richardson's estimates the realization of such an ambition would have needed the combined force of 64,000 human calculators.

Bjerknes' graphical and Richardson's numerical solutions proved difficult and never reached the status of routine application in weather prediction. But Bjerknes did go on to describe weather phenomena that changed meteorological understanding fundamentally. He and his students described larger patterns of air flow and discovered the importance of air masses, cyclones (very large rotating air flow systems) and polar fronts. Weather could not simply be conceived as a state of the atmosphere at specific locations (on or above ground). The development of weather, in contrast, was a geographically extended phenomenon reaching across continents.

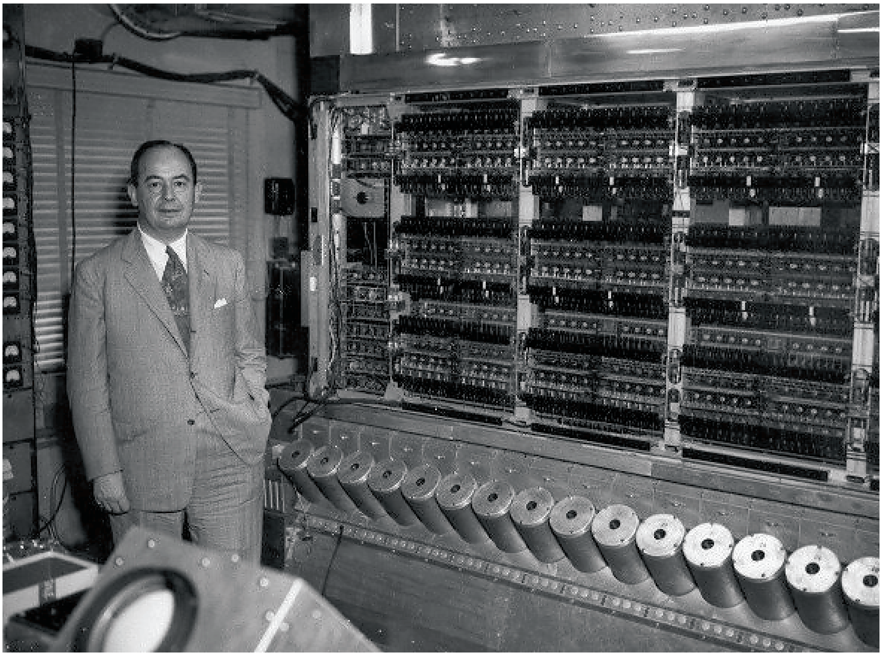
The exploration of the higher atmosphere and the description of extended weather systems also left their mark on climatology and gave rise to a broadened view of climate. First, a climatology of the higher atmosphere emerged, which was founded on the availability of a growing body of meteorological data from higher layers of the atmosphere. Second, it had become clear that an understanding of the causes of climate required a departure from the strict focus on locality and instead demanded consideration of the wider geographical extension of weather systems, which could be in the range of thousands of kilometres. The concept of climate slowly shifted from being a predominantly geographical concept linked to specific locations to a more dynamical concept linked to typical weather systems and extending over considerable distances. The Swedish meteorologist Tor Bergeron, a member of Bjerknes' Bergen school, consequently demanded a "dynamic climatology" in 1930. The dynamic aspects of climate did not only concern the causes of climate produced by a dynamic atmosphere. This also opened up the possibility of thinking about longer-term and more fundamental changes of climate – a possibility, which the "average-climatology" of von Hann with its emphasis on the stability of climate did not account for.

In the 1930s the International Meteorological Organisation (a predecessor of the World Meteorological Organisation) adapted the official definition of the term "climate" in accordance with this new thinking. This new definition described "the average state of the atmosphere above specific locations *within a specific period of time*". The expression "specific period of time" was recommended to be taken as a period of thirty years. A change of climate within a few decades now became an acknowledged climatologic possibility, and a legitimate scientific consideration. The German climatologist Hermann Flohn attempted to integrate the features of classical and dynamic climatology around 1950 and suggested the term “modern climatology”. This attempt, however, failed in the long term, since it soon became apparent that conceptions of climate in classical climatology and in dynamic climatology did not match. The physical and dynamic conception of “climate” proved incompatible with classical climatology’s geographical interpretation. So, this led to the situation where there were two rather different definitions of climate in circulation, a geographical one, interpreting climate as a set of characteristics of a geographical location, and a meteorological one focused on the physical characteristics of extended weather systems.

4. The rise of climate change research

It still took some time before the concept “climate change” was recognised widely. But technological progress, military interest and scientific ambition all helped the process. During war time rapid progress was made in the development of new calculation machines. The US Army needed such machines for the calculation of ballistic tables. John von Neumann, an outstanding mathematician, was involved in these developments. Early on he recognized the potential of these machines, soon to be called “computers”. They were capable of performing up to 5,000 operations per second, and it was not long before von Neumann began to ask what these machines could be used for outside the existing military application? One answer was weather prediction. In 1946 von Neumann assembled a team of brilliant young scientists. Four years later the first promising weather calculations had been performed. Von Neumann’s team had set off with Bjerknes’ differential equations (as did Richardson 30 years earlier), introduced drastic simplifications and transformed the mathematical operations for the numerical solution of the equations into computer code. Thus, the first meteorological computer model was based on physical theory and used to simulate the development of weather on the computer.

Computer simulation for weather forecasting made quick progress in the following years. Weather services adopted and extended early computer models. In the early 1960s computer-based forecasts had reached the same performance as traditional methods of weather prediction. But, meteorological models did not only revolutionize weather prediction. Their impact on climate research was more far reaching. It started in 1956 with a bold computer experiment. Norman Phillips, a young member of von Neumann’s



John von Neumann in front of one of the early computers that were part of the breakthrough in climate change prediction.

modelling team, attempted to use the meteorological model to simulate the development of the weather, not for single days, but for a longer period of time in order to investigate longer-term processes of weather and climate. Due to limited computer capacity, Phillips had to introduce further simplifications into the model. He neglected vertical air movements and the distinction of land mass and ocean. He also started his simulation with the unrealistic initial condition of equal temperature and a static atmosphere with no air movements over the whole globe. This idealization meant that he did not need to begin with a large initial data set. In the simulation run air masses were set in motion solely by solar radiation and the earth's rotation. After several simulated days a pattern of cyclones emerged – very similar to the cyclones in the real atmosphere.

Phillips' computer experiment was ground breaking. His model represented the first version of a model type which soon came to be called the General Circulation Model (GCM). GCMs are global simplified versions of weather models that can be used for simulation runs over a long period of time in order to study the development of climate. GCMs can also be used as experimental instruments. Model parameters or input data can hypothetically be changed (such as solar radiation or the carbon dioxide concentration in the atmosphere) and the impact of these changes on (model-) climate can then be investigated. The prospect of so-called "computer experiments" was met with a mixture of enthusiasm, and curiosity, among scientists. And it soon became apparent that it was now possible to simulate experiments that would be impossible in the real world (such as doubling the carbon dioxide concentration in the atmosphere). After Phillips' pioneering experiment several research groups engaged in GCM development for climate simulation. These included a group at the US Weather Bureau (which was later moved to the Geophysical Fluid Dynamics Laboratory at Princeton University) and further groups at the University of California in Los Angeles, the Laurence Livermore National Laboratory at Livermore, California, and the National Centre of Atmospheric Research at Boulder, Colorado. The first climate models outside the USA emerged about ten years later in the early 1970s.

By the end of the 1960s GCMs were already widely acknowledged as a central tool in climate science. Climate models created new opportunities, which increasingly shaped scientific efforts and interests. This kind of model, for example, provided an excellent means to investigate the impact of changes in carbon dioxide concentrations in the atmosphere by way of simulation. One common new strategy was the simulation of the global climate for double the existing concentration of carbon dioxide. While such experiment could not be performed in nature, the computer proved a perfect playground for investigating the effects of such global change. A series of simulation experiments in the 1960s and early 1970s suggested that a doubling of carbon dioxide concentration would increase the global average temperature by 1 to 6°C. Arrhenius' and Callendar's calculations, thus, were confirmed. But this time, the interest in these results was much greater in the scientific community than in Arrhenius' or Callendar's time. The historian Paul Edwards has suggested that the prediction of climate change by computer simulation benefitted greatly from the enormous prestige of the computer. But it is also possible that the newly emerged and persistent interest in climate change owed as much simply to the availability of a fascinating versatile new research instrument (the computer), which was ideally suited for the investigation of climate change. Arrhenius and Callendar did not possess such an instrument.

The situation of researchers using climate simulation models in the 1960s or 1970s was very different to the situation of Callendar 40 years earlier or Arrhenius at the end of the nineteenth century. These late twentieth-century researchers were not working totally on their own; and they did not have to stand their ground in a foreign scientific community. Climate simulation based on computer models formed the core of a new and thriving research community. Computer power increased at a rapid pace, and these ever more powerful computers enabled scientists to enlarge their models and include even more detail in ever more comprehensive simulation runs. The philosopher Paul Humphreys suggested, that scientific progress today is strongly dependent on progress in computer technology. Similarly, we can conclude, that progress in computer technology strongly and continuously fuelled scientific research. While climate models in the 1970s were limited to processes in the atmosphere, by the close of the twentieth century, oceans and other areas of water (hydrosphere), biological processes (biosphere), ice and snow (cryosphere) and soils and the earth's crust (pedosphere and lithosphere) were all be included in the models. Climate models became "earth-system models", which included the exchange processes between the atmosphere and other components of the "earth system". At the same time, increased computer power facilitated an increased resolution of the models. In 1990 the models were based on grids with a grid cell length of about 500 km, by 1995 this length was reduced to about 250 km, by 2001 to about 180 km and in 2007 to about 110 km. Likewise, the number of researchers involved in climate modelling increased from some 20 in the early 1960s to several thousand at the end of the millennium.

In summary we may conclude that the analysis of 150 years of research on climate reveals fundamental shifts and changes. Research interests shifted from a geographically oriented classical climatology to a physically oriented climate change science. This shift was associated with a dramatic change in the meaning of the term "climate". Until well into the twentieth century "climate" represented a geographical term, describing the collective effect of local atmospheric phenomena on human senses. The term "climate" only made sense in relation to specific locations. Climates differed in different locations, but remained stable over time. At the end of the twentieth century the term climate had lost its association with specific locations and had become a global category. The understanding of the scientific term "climate" now did not only involve large-scale weather systems, but the whole earth system. While geographical interest in climate faded almost completely (or was not visible anymore), interest in climate change dominated research efforts in the second half of the twentieth century. This shift in interest can not simply be explained by stronger evidence for climate change. Knowledge about the effect of increased carbon dioxide emissions existed in the late nineteenth century. And evidence supporting predictions of rising temperatures was as strong around 1940 as it was in the year 2000. In fact, it was a number of scientific, technological and social factors that helped make climate change of interest, and of import, to the scientific community, politicians and public alike. Such, factors included the conquest of the higher layers of the atmosphere (by flight technology and meteorological measurements) and the advent of the computer, which turned out to be a tremendously powerful research machine.

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