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978-0-521-73255-0 — The Climate Crisis: An Introductory Guide to Climate Change
David Archer , Stefan Rahmstorf
Excerpt
More Information

1 Retrospective: what we knew and when we knew it

The science of climate change has a long history, but progress has accelerated amazingly in the last few years. The theory of the greenhouse effect is almost two centuries old, discovered by mathematician Joseph Fourier in 1827. Later, in 1896, Svante Arrhenius estimated how sensitive the climate would be to changes in the concentration of the greenhouse gas carbon dioxide (CO_2) in the atmosphere. Arrhenius' answer of 4 to 6 °C of warming from doubling CO_2 was not far off from our current estimate of 2 to 4.5 °C.

Progress and contributions to climate change science have accelerated because science itself is growing exponentially, and also because of the importance of the topic to human well being and planning. Stanhill (2001) assessed the number of scientific papers on the topic of climate change, and found that the number of papers per year has been doubling every 11 years since the 1950s. He estimated that, globally, 3 billion US dollars were spent annually on climate change research as of about the year 2000. For scale, the net income of the Exxon Mobil Company was $40 billion in 2007.

The massive task of synthesis and summary of this exploding research effort falls to the Intergovernmental Panel on Climate Change, or IPCC. This organization was founded in 1988 by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), and charged with assessing the scientific, technical, and socio-economic information relevant for understanding the risk of human-induced climate change. Most of the work of IPCC is done by thousands of research scientists at universities and national laboratories around the world.

The participants are divided into Working Groups. Working Group I is in charge of scientific assessment of global climate science. Working Group II deals with the potential impacts of climate change to socio-economic and natural systems. Working Group III deals with options for avoiding (what they call mitigating) the effects of global warming. The working groups are divided into teams of people who essentially read the peer-reviewed published scientific literature and summarize the results in individual chapters.

IPCC does not fund new scientific work, but it stimulates new research by highlighting existing uncertainties in climate change research, and also by proposing future scenarios of the drivers of climate change (greenhouse gas concentrations, aerosol emissions, etc.), which climate modelers are requested to run through their models, so that the models can be compared on a level playing field. Twenty-three models from groups around the world participated in the intercomparison exercise, running a variety of different scenarios for the drivers of climate change in the coming century.

The IPCC publishes reports called Scientific Assessments summarizing the state of the field every five years or so. The first IPCC report was in 1990, called the *First Assessment Report* or FAR. Subsequent updates were released in 1996 (the *Second Assessment Report* or SAR), 2001 (the TAR), and now the current, *Fourth Assessment Report*, called AR4, released in 2007, is the topic of this book. Most of our discussion will focus on the results of the Working Group I report on global climate science. Chapter 8 will briefly review the products of Working Group II (impacts of climate change), and Chapter 9 will address Working Group III (avoiding climate change).

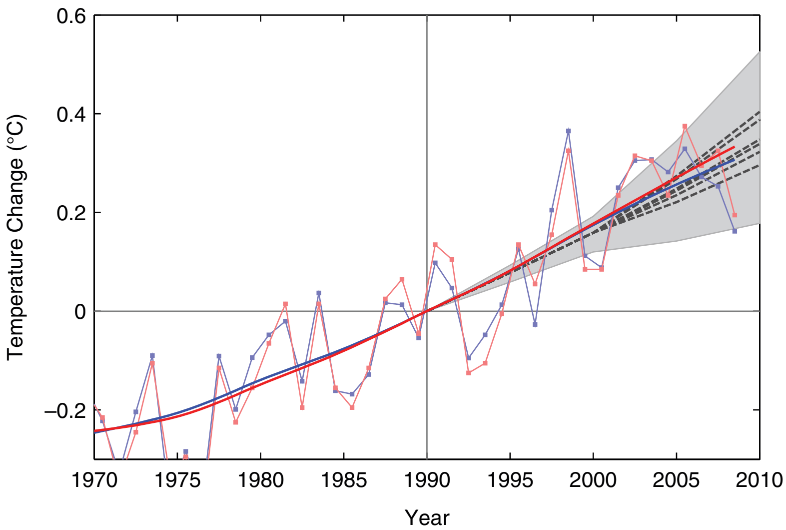

Figure 1.1 Climate projections published in the third IPCC report of 2001 compared to the actual global temperature change since 1970. The measured values are shown in red (NASA) and blue (Hadley Centre), with dots showing annual values up to 2008, while the thick curves show the trend line. The IPCC scenarios start in 1990 and are shown as black dashed lines; the broader gray band is the uncertainty range.

The short *Summaries for Policy Makers* (SPM) capture most of the public attention – not surprisingly, since the full reports are hefty and not easy to read. The summaries also go through an interesting process of line-by-line consensus approval with government representatives from around the world, who gather with IPCC scientists for a week-long meeting for this purpose. In this way, governments are involved and get a chance to raise their concerns about particular phrases in the summary. Of course, they cannot alter the science, since the summary must always reflect what is in the main report, but in some cases government representatives have weakened some of the language used by the scientists who drafted the summaries. More often, however, government representatives are concerned about the scientists' language being too technical: "My minister will not understand this sentence" was a repeated intervention during the approval process for the Working Group I summary in Paris in February 2007. Since both the draft and the final versions of the SPMs are accessible on the Internet, the influence of the government approval process is transparent and can be tracked.

The *First Assessment Report* in 1990 did not find evidence for human-induced warming sufficient to rise above the noise of natural climate variability. However, they predicted that global warming should be detectable by the year 2000. Detection of global warming came early, in 1995, as the *Second Assessment Report* concluded, "the balance of evidence suggests a discernible human influence on global climate." This conclusion was strengthened in the 2001 *Third Assessment Report*, to read: "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."

All of the reports predicted rising, record-breaking heat, and all of the reports have been correct in this prediction. The *Fourth Assessment Report*, AR4, concludes that it is 90–99% likely that global warming since 1950 has been driven mainly by the buildup of carbon dioxide and other heat-trapping greenhouse gases, and that more warming and rising sea levels are on the way.

Awareness of the past

Mankind has been aware of the potential for changes in climate for over a century. Louis Agassiz (1837) proposed that the mountains of his native Switzerland had once been covered with large ice sheets like those in Greenland or Antarctica. His hypothesis explained the presence of rocks called exotics, different from the local bedrock but apparently transported from different bedrock far away. Agassiz also noted scratch and etch marks that seemed similar to marks a large sheet of flowing ice would make.

It must have been rather frightening to imagine the countryside as he knew it crushed and wiped out beneath a giant ice sheet. His proposal met resistance from the prevailing view, supported by religious doctrine, that the biblical flood was responsible for shaping the landscape. Eventually the ice age hypothesis was accepted.

Changes in atmospheric CO_2 were considered a possible cause of the ice ages, for example by Svante Arrhenius in 1896, but another potential driver for ice ages was and still is considered to be wobbles in the Earth's orbit around the sun. The first orbital theory of climate dates to James Croll in 1864, who proposed that variations in the intensity of sunlight reaching the ground in the Northern Hemisphere winter are responsible for the waxing and waning of ice sheets. Milutin Milankovich modified the theory in 1914, while he was a prisoner in the First World War, to its current form by proposing that it is sunlight intensity in the Northern Hemisphere summer, in particular, which drives the ice age cycles.

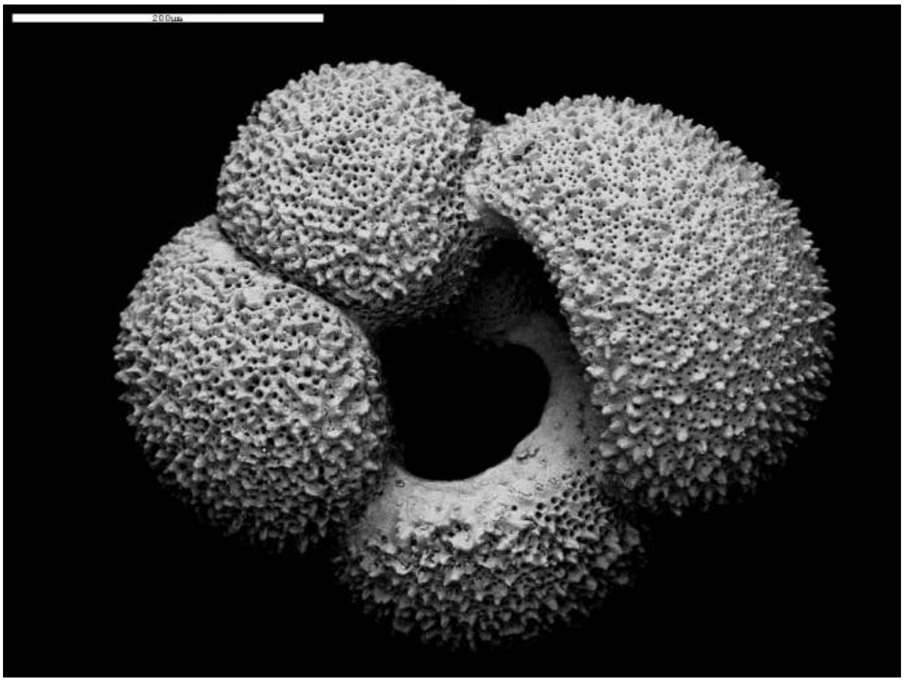

Figure 1.2 The microscopic shell of a planktonic foraminfera, *G. bulloides*.

The comings and goings of the ice ages are recorded in deep sea sediments and in ice sheets. The first sediment climate records were developed in the 1950s, based on measurements of the isotopes of oxygen in shells composed of limestone (calcium carbonate), $CaCO_3$ (Figure 1.2). Oxygen has several different isotopes, different types of atoms which all behave chemically as oxygen but they differ somewhat in how heavy they are. An ice sheet grows from water that evaporates from the ocean, the atmosphere acting like a giant still. The distilled water that makes it to the ice sheet has fewer of the heavy oxygen isotopes relative to the light ones; it is what is called "isotopically light." When the ice sheets grow large, the water left behind in the oceans tends to be isotopically heavy. The oxygen in $CaCO_3$ shells that deposit on the sea floor contains a record of the oxygen isotopic variations of the ocean, like tape in a tape recorder. In the 1970s it was found that the growth and decay of the ice sheets correlate in time with Milankovich's orbital variations, providing strong support for a role of orbital variations in determining Earth's climate.

Ice cores also contain time-detailed records of past climate variations, including notably an archive of actual samples of the ancient atmosphere, in which the concentrations of gases like CO_2 and methane (CH_4) can be measured. In the 1980s it was discovered that ice core atmospheric CO_2 and methane concentrations both rise and fall in concert with the amount of ice in the ice sheets, amplifying the climate extremes of the ice ages. The correlation between local temperature in Antarctica, and atmospheric CO_2, now extended back 650,000 years through seven glacial cycles (Figure 6.6), is compelling evidence for a role for CO_2 in global climate. The cause of the CO_2 changes is not well understood even today. The whole caboodle still marches in time with Milankovich's orbital variations, suggesting that somehow the natural carbon cycle amplifies the orbit's primary driving of the ice sheets.

It has become increasingly apparent in recent decades that climate does not respond linearly to wobbles in the Earth's orbit. It's not as simple as that. Through the past million years or so, the volume of ice through time has a much stronger 100,000 year cycle than is found in Milankovich's orbital forcing. This and other quirks of the history of ice sheets in the last two million years can be explained if we suppose that ice sheets have a tendency to grow to a certain size and then collapse quickly.

In the 1990s the Greenland ice cores revealed that the climate of the glacial world was much less stable than the warm climate of the past ten thousand years. The climate of the high northern latitudes in particular seemed to flip between different states, in what are known as "abrupt climate changes." These observations are described in Chapter 6. The abrupt climate transitions typically took less than a few decades, while the climate states before and after may have lasted for a thousand years. One could argue that the IPCC forecast for a generally smooth climate transition may be a best-case scenario, because of the lack of any abrupt surprise climate flips such as these.

The data for reconstructing the climates of the deep past have grown more comprehensive and diverse in recent years. The original core from which the glacial CO_2 cycles were discovered, from a site called Vostok in Antarctica, was extended back to 650,000 years ago in 2004 (Figure 6.6). Another new data archive comes from a site called Dome C, providing a very detailed CO_2 record of the last 2,000 years (Figure 6.7). There are also many new reconstructions of the last 1–2 thousand years from tree rings and boreholes that have been published just in the last few years (Chapter 6).

New ocean sedimentary climate records have been developed that have the time resolution to show abrupt climate changes. Ocean sediments tend to be smoothed by the actions of burrowing animals mixing up the sediment, but this problem can be avoided by finding sediments from places with no oxygen dissolved in the water, where animals cannot live, or sediments that accumulate very quickly. Sedimentary records, and also ice core records in mountain glaciers, document the abrupt onsets of regional drought events

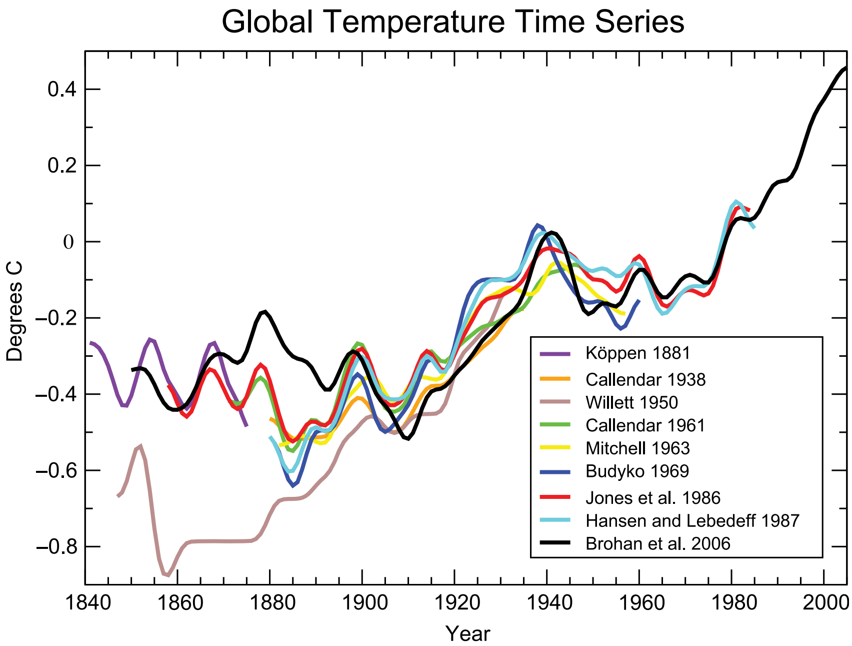

Figure 1.3 A comparison of different reconstructions of the global average temperature of the Earth.

through the Holocene, which had previously appeared to be a time of stable climate, based on ice core data.

Turning our focus back to historic times, Figure 1.3 shows reconstructions of the Earth's temperature that have been attempted in the last century. Weather observations date back several centuries, but it has been a big, ongoing job to collect, check, and then average the temperature data. Urban data are excluded to avoid bias from the urban heat island effect, although the corrections are small (Chapter 3). Sea surface temperatures need to be corrected for the method of measuring temperature, which changed from the traditional method, using cloth buckets to collect surface seawater, to automatically measuring the temperature at the intake of an engine cooling system. In spite of these differences, the various records of global average surface temperature changes, created over the past decades, show a remarkable uniformity.

Understanding climate

Scientific understanding of the basic physics of the greenhouse effect, and the potential for global warming as a result of CO_2 emission, has been building for over two centuries. The idea of the greenhouse effect, and its name, was invented by Joseph Fourier, a mathematician in Napoleon's army, in 1827. The discovery that energy can be transported by invisible infrared radiation had only been discovered in 1800 by Sir William Herschel, an astronomer. Fourier reasoned that if the outgoing infrared energy is blocked by gases in the atmosphere, analogous to a pane of glass in a greenhouse, the temperature of the surface of the planet would rise. The glass warms the interior by absorbing the light from the ground, and by shining its own light back down to the ground.

We should note that greenhouses also warm up by preventing warm air inside from rising and carrying away their heat. For this reason the greenhouse effect is perhaps not ideally named, but the idea behind it is essential for explaining the natural temperature of the Earth, which would be frozen all the way to the equator if it were not for Fourier's greenhouse effect. Venus and Mars are also warmed by their CO_2 atmospheres. The theory of the greenhouse effect is undisputed in scientific circles.

Carbon dioxide, methane, and water vapor were identified as greenhouse gases in 1859 by John Tyndall. A gas acts as a greenhouse agent if it interacts with infrared light, absorbing the light energy and converting it to heat, and in the opposite direction, radiating heat away as infrared light. The atmosphere is mostly made up of nitrogen and oxygen gases, N_2 and O_2, which are transparent to infrared light and therefore not greenhouse gases. Only the more complex molecules, containing three or more atoms, or two dissimilar atoms, act as greenhouse gases.

Svante Arrhenius in 1896 calculated that doubling CO_2 in the atmosphere would increase the temperature of the Earth by on average 4–6 °C. Data to base a calculation upon were scarce and crude. It wasn't known at that time how much infrared radiation the greenhouse gases would absorb, for example. Arrhenius used measurements of the infrared brightness of moonlight to figure out how much infrared radiation the gases in the atmosphere absorb. When the moon is directly overhead its light shines through a thinner layer of air than when the moonlight comes in obliquely. In spite of the crudeness of the data available and a few questionable assumptions, Arrhenius got the answer basically correct. The equilibrium warming from doubled CO_2 is a quantity now called the climate sensitivity. Guy Stewart Callendar estimated the climate sensitivity again, in 1938, to be 2 °C. The current most likely range for it is 2–4.5 °C, with a best estimate of 3 °C (Chapter 7).

Both Arrhenius and Callendar predicted correctly an important phenomenon called the water vapor feedback. Water vapor is a greenhouse gas; in fact it is a stronger greenhouse gas in our present atmosphere than

CO_2 is. If the water vapor concentration gets too high for a particular temperature, in other words, if what we call the relative humidity exceeds 100%, water tends to condense and it will rain or snow. In contrast to CO_2, which accumulates in the atmosphere from human emissions, the amount of water vapor in the air is regulated quickly by the water cycle, so that lawn sprinklers and swimming pools do not have a strong impact on the water vapor content of the atmosphere as a whole.

The water vapor feedback effect arises because the amount of water vapor that air can hold depends very sensitively on the temperature. A warming of the atmosphere, caused by rising CO_2 concentrations for example, allows the atmosphere to hold more water vapor. Because water vapor is a greenhouse gas, the additional vapor leads to further warming. The strength of the feedback is hard to predict precisely, because the relative humidity of the atmosphere is not always exactly 100%. As air rises, it cools and the water vapor is wrung out, leading to clouds and rain. When the air sinks again it has a very low relative humidity. The water vapor concentration in a parcel of air therefore depends on the recent history of the air, in other words the weather.

Because the air might circulate differently in a different climate, there is a possibility that the relative humidity of the atmosphere might change a bit, in either direction, making the water vapor feedback stronger or weaker. The earliest studies made the assumption that the relative humidity of the atmosphere remains about the same as the air warms. This assumption has since been corroborated by more recent numerical models (in which the humidities are determined by the models' own water cycles) and by meteorological data. The water vapor feedback more than doubles the amount of warming we'd get from CO_2 in a totally dry atmosphere.

Ice plays many roles in Earth's climate. Ice and snow tend to reflect sunlight, and therefore act to cool the Earth. When ice melts, more of the sunlight is absorbed by the darker ground or ocean underneath the ice. Melting ice therefore acts to amplify an initial warming, in a process called the ice albedo feedback. The word albedo refers to the reflected fraction of sunlight. The planet Venus is very reflective because of its clouds: we say it has a high albedo.

The ice albedo feedback was predicted by Arrhenius in 1896. Climate records from the past few decades show the effect of the ice albedo feedback already, in that warming is more intense in the Arctic than it is on the planet as a whole. The Arctic Ocean is projected in some models to be seasonally ice-free in the coming decades, representing one of the clearest examples of a "tipping point" in the near-term future. Sea ice in the Southern Hemisphere has not been melting the way it has in the North, so there has not been much change in albedo in the Southern Hemisphere. The observed cooling in the

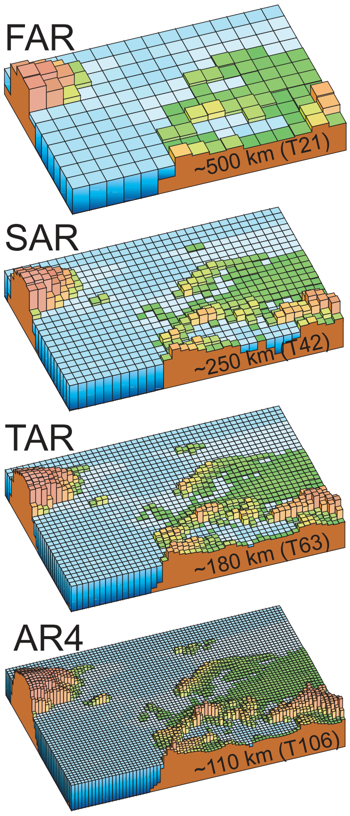

Figure 1.4 The climate models used in the sequence of Assessment Reports have become more detailed with the growth of computer power. These levels of detail are used for short-term climate projections. Century time scale climate simulations are typically done using the resolution at the previous level.

interior of the Antarctic may be caused by changes in atmospheric circulation resulting from the ozone hole, which is most intense in that region.

The specifics of the climate change forecast, the regional climate changes, and the impacts on the water cycle, for example, are derived from numerical models of the atmosphere, ocean, ice, and biosphere coupled systems. Atmosphere and ocean flows are turbulent, and the amount of heat and other properties that they carry depends on the details of this flow. The models used to forecast climate change are cousins to the models used to forecast the near-term weather. Weather forecasts have become demonstrably better since the 1990s, an indication of the growing sophistication of the climate models as well.

In general, the fidelity of the forecast, and the characteristics of the simulation, improve with increasing detail in the model. However, increasing the amount of detail in a computer climate model slows it down dramatically. Doubling the number of grid points in all three dimensions slows the code down by more than a factor of ten. Working in our favor however is the explosion in computer power since the 1990s, enabling the resolution of climate models to expand as shown in Figure 1.4.

In spite of increasing computer power, many processes within the climate system are impossible to predict from first principles, as would be ideal. Clouds, for example, depend on meter-scale gusts of wind, and on micrometer-scale interactions between cloud droplets. These processes will not be explicitly resolved on even the fastest computers within the foreseeable future, and so the end result, the clouds, must be based on larger-scale observations of cloudiness, rather than the true microscopic mechanisms that really control the evolution of the cloud. The cloud parameterizations are tuned until they reproduce the observed distribution of clouds. Unfortunately, changes from one apparently reasonable cloud parameterization to another are sufficient to make a large difference in the climate sensitivity predicted by the model.

Given the imprecise and subjective nature of climate models, significant progress has been made by the process of model intercomparison. Independent models written by separate teams of researchers incorporate