Chapter 1

Climate Change Science Overview

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Introduction

This chapter outlines the current state of scientific knowledge regarding the climate system and the effects of human activities on climate. Although uncertainty remains regarding knowledge about climate, the basic processes that cause climate change are scientifically well established, and human activities have been identified with very high confidence as the main driver of most observed climate-induced trends during the last several decades. Conclusions such as these are based on the vast preponderance of accumulated scientific evidence. To understand complex systems science like the study of climate change, it is essential to distinguish such conclusions from hypotheses that can be "falsified" by one or even several lines of argument that seem to contradict the mainstream consensus. This is how simple science used to be done—for example, testing whether the liquid in a tube is acidic or basic. One piece of litmus paper can falsify a wrong preliminary hypothesis. While it can take decades to reconcile incomplete elements of complex systems analysis, rarely will a few contrary results entirely overthrow a consensus built on decades of consistent lines of evidence.

Throughout this chapter, many research findings we refer to are taken from the multiply-peer-reviewed, government-approved Intergovernmental Panel on Climate Change (IPCC) Assessment Reports, which present the best approximation of a worldwide consensus on climate change science every five to six years. One important feature of IPCC reports is the quantified assessment of the likelihood of each major conclusion, and the explicit assignment of the authors' confidence in the underlying science to back up each conclusion. This practice clearly separates out aspects that are well established from those that are better described by competing explanations and from those best labeled as speculative. This contrasts markedly from most of the media and political debates in which well-established conclusions are often conflated with speculative ones, and public confusion results. Box 1.1 presents the likelihood and confidence definitions from the 2007 IPCC Fourth Assessment Report (AR4).[1]

Box 1.1

The IPCC defines the likelihood of an outcome or a result as: Virtually certain (greater than 99 percent probability of occurrence), extremely likely (greater than 95 percent), very likely (greater than 90 percent), likely (greater than 66 percent), more likely than not (greater than 50 percent), unlikely (less than 33 percent), very unlikely (less than 10 percent), and extremely unlikely (less than 5 percent).

The IPCC defines the level of confidence in the correctness of the science underlying a conclusion as: Very high confidence (at least a 9 out of 10 chance of being correct), high confidence (about an 8 out of 10 chance), medium confidence (about a 5 out of 10 chance), low confidence (about a 2 out of 10 chance), and very low confidence (less than a 1 out of 10 chance).

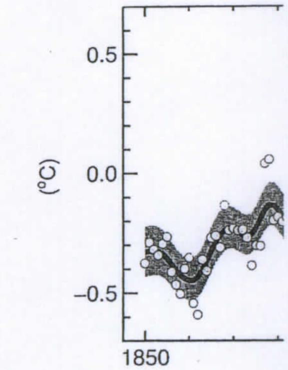
The Global Temperature Record

Modern temperature records date back to the mid-nineteenth century, when thermometers became accurate and widespread enough to allow scientists to calculate a meaningful global average temperature. These records show (figure 1.1) that the Earth's average surface temperature has increased by about 0.75 degree Celsius (around 1.4 degrees Fahrenheit) since the mid-nineteenth century (with an uncertainty of about a tenth of a degree Celsius).[2]

Year-to-year variation in temperature cannot override this long-term upward trend in global average temperature. Unfortunately, short-term variability in the temperature record is often inappropriately used to "refute" long-term climatic trends. Climate, however, refers to the state of atmospheric conditions over decades or longer, while weather refers to shorter-term variations in atmospheric conditions. Thus, the IPCC description of the warming trend of past century or so as "unequivocal" is indeed appropriate, and even decadal-scale exceptions do not disprove this long-term fact.

Looking back into history can tell us more about how the current anthropogenic (or human-caused) changes compare to naturally induced changes in the past, both in magnitude and in rate. Paleoclimatologists use proxy variables that vary with temperature to approximate temperature records that stretch back hundreds, thousands, and even millions of years (see figure 1.2). These proxies consider diverse factors such as tree rings, the extent of mountain glaciers, changes in coral reefs, and pollen in lake beds. Although there is considerable uncertainty in temperature, the averaged trend over the last 1,000 years is a gradual temperature decrease over the first 900 years, followed by a sharp upturn in the twentieth century (shown also in figure 1.1). The question is, Why?

In particular, there are three typical explanations of observed global mean surface air temperature trends: (1) natural internal variability, in which energy exchanges among atmosphere, oceans, ice sheets, and ecosystems cause random, unpredictable background noise; (2) natural forcings in the Earth's radiative energy input from volcanic dust veils or solar energy fluctuations; and (3) anthropogenic



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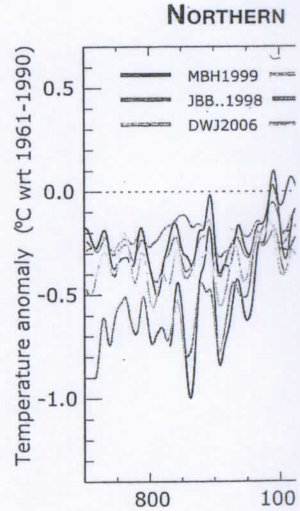

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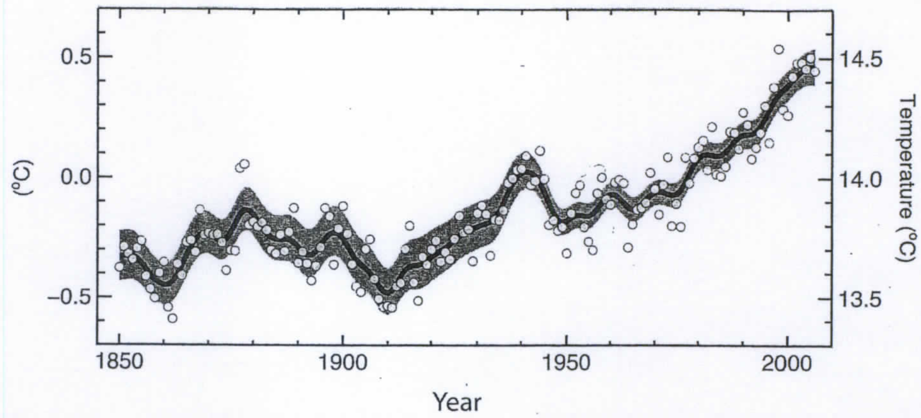


FIGURE 1.1. Observed global average temperature record (since 1850), shown relative to the average for 1961–1990 (vertical axis on the left), as well as in absolute terms (vertical axis on the right). Smoothed black line represents decadal average values, circles represent yearly values. Shading represents uncertainty in observations. Source: Intergovernmental Panel on Climate Change (IPCC), 2007(a), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon et al., eds., Cambridge University Press: Cambridge, United Kingdom.

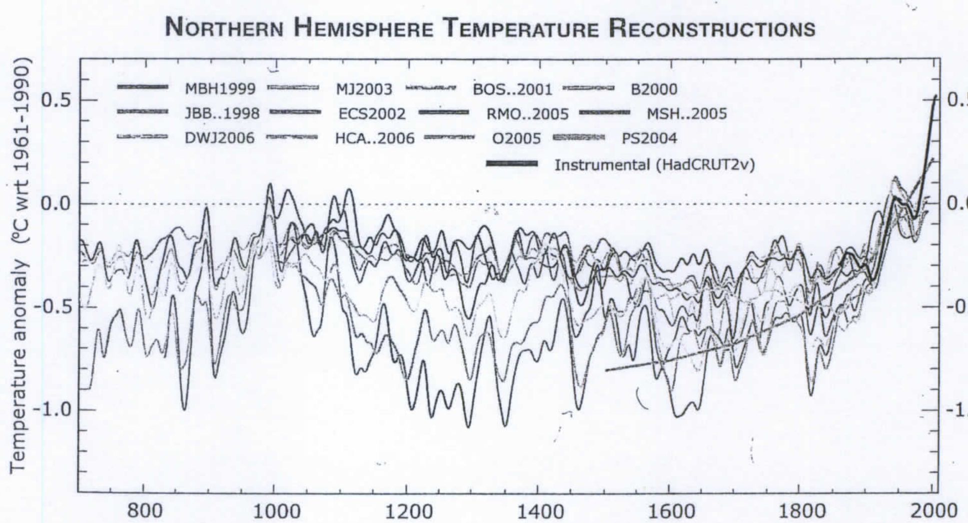


FIGURE 1.2. Records of northern hemisphere temperature variation during the last 1,300 years relative to the 1961–1990 average using multiple proxy records. Observed temperature record since 1850 shown in black. Source: Intergovernmental Panel on Climate Change (IPCC), 2007(a), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon et al., eds., Cambridge University Press: Cambridge, United Kingdom.

forcings, such as increased greenhouse gases, altered atmospheric aerosols (e.g., dust and smoke), and land-use changes.

A Natural Climate Variation?

Is it possible that natural variability and natural forcings of the Earth's climate could produce the temperature record of figures 1.1 and 1.2? Using a variety of methods to detect the human "fingerprint" on observed warming trends, scientists are finding overwhelming evidence that the answer to this question is "no" (see chapter 2).

Scientists can also use computer models of the climate system (see below) to investigate the contribution of natural and human factors to the observed warming. Figure 1.3 shows a comparison of the global average surface temperature record for the twentieth century (black line) with two sets of climate model simulations of this time period. The gray lines represent simulations that are driven only by estimates of purely natural forcings—solar variability and volcanic activity (see Solar Variability and Aerosols below). The range of simulations indicates an estimate of the degree of uncertainty in the model calculations. The estimated temperature variation due to natural forcing alone does not show an overall warming trend and is clearly a poor fit to the actual surface temperature record, especially in the second half of the century when temperatures made a significant upturn. The lighter lines represent simulations that also incorporate anthropogenic factors—emissions of greenhouse gases and aerosols. The fit between these simulations and the observed record is far better; they strongly suggest that the temperature changes observed in the twentieth century, particularly the rise of the past few decades, cannot be explained without anthropogenic greenhouse gas emissions as a significant causal factor.

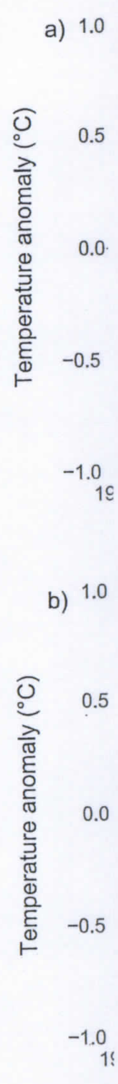
Taken together, these and many other fingerprint analyses provide very strong evidence that the observed changes in climate over at least the past several decades are anthropogenic.[3] This has led the IPCC to conclude that most of the warming observed over the last fifty years is attributable to human activities and, in addition, that the influences of anthropogenic climate change are now identifiable on warming ocean temperatures, changes in the life cycles of plants and animals (see chapter 3), atmospheric circulation patterns, and the increasing intensity of some extreme weather events.[4]

Keeping the Earth Warm

What ultimately determines climate and specifically the Earth's temperature? That question is at the heart of climate science and of the issues surrounding anthropogenic climate change.

About half of the light energy from the sun penetrates the atmosphere and is absorbed by the Earth's surface. The surface warms and re-emits some of the energy as infrared radiation. Certain naturally occurring gases and particles—greenhouse gases—absorb 80 to 90 percent of the infrared radiation emitted at the surface and radiate heat in all directions, both up to space and back down toward the surface, warming the surface further. This feedback cycle between the Earth's surface and the atmospheric greenhouse gases continues until the infrared radiation released to space is in balance with the sources of radiant energy.

Because the atmosphere functions, in a crude sense, like the heat-trapping glass of a



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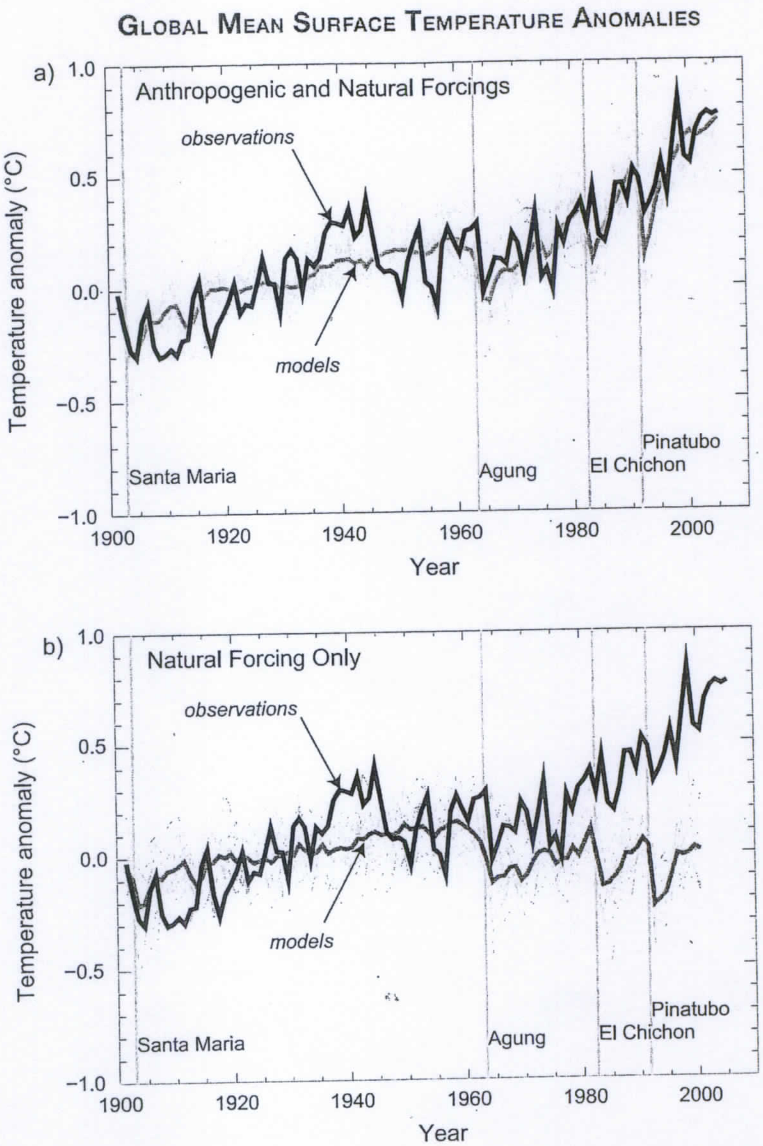

Figure 1.3. Observed changes in surface temperature compared with results simulated by climate models using natural and anthropogenic forcings. Decadal averages of observations are shown for the period 1906–2005 (black lines) relative to the corresponding average for 1901–1950. Gray lines depict model estimates; the ranges of estimates reflect model uncertainty. Gray lines use only natural forcings due to solar activity and volcanoes (dark gray line is multimodel average). Gray lines use both natural and anthropogenic forcings (dark gray line is multi-model average). Major volcanic eruptions are shown in both panels, corresponding to temporary cooling episodes. Source: Intergovernmental Panel on Climate Change (IPCC), 2007(a), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon et al., eds., Cambridge University Press: Cambridge, United Kingdom.

greenhouse, this heating process has earned the nickname "greenhouse effect." The natural greenhouse effect from gases and clouds effectively raises the Earth's surface temperature by 33 degrees Celsius (59 degrees Fahrenheit), which supports life as we know it on the Earth. However, increasing concentrations of atmospheric greenhouse gases due to human activities are intensifying the greenhouse effect and further increasing the Earth's temperature.

Greenhouse Gases Past and Present

Human activities add to the atmospheric concentrations of a number of naturally occurring greenhouse gases and introduce other potent greenhouse gases that are not naturally occurring. Increasing concentrations of the greenhouse gas carbon dioxide (CO_2) due to human activities, primarily the burning of fossil fuels but also deforestation and other land-use changes, have contributed most to the intensification of the greenhouse effect. As shown in figure 1.4, before the Industrial Revolution, CO_2 concentrations were relatively stable for roughly 10,000 years, varying between 260 and 280 parts per million (ppm). In the last 150 years, atmospheric CO_2 concentrations have increased by more than 35 percent, from around 280 to around 380 ppm. The reality of this CO_2 increase is well documented and is well-established science.

Carbon dioxide entering the atmosphere does not just sit there. Huge quantities of carbon circulate between the atmosphere, the ocean, and land ecosystems. As the burning of fossil fuels and carbon dioxide emissions have increased, flows of carbon from the atmosphere into the ocean and into land ecosys-

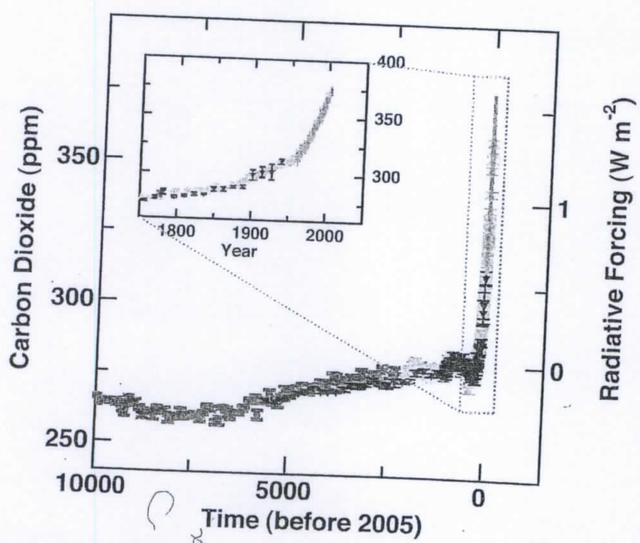

FIGURE 1.4. Atmospheric concentrations in parts per million (ppm) of carbon dioxide during the last 10,000 years and since 1750 (inset panel). Measurements from ice cores (different shades for different studies) and atmospheric samples. Corresponding radiative forcing is shown on the right side.

tems have also increased, but by a smaller amount. Currently, about half of the annual anthropogenic carbon dioxide emissions are taken up by ocean and land ecosystems. However, scientists have observed a decrease in the fraction of anthropogenic emissions absorbed by ocean and land ecosystems, and expect that fraction to continue to decrease as these "sinks" become saturated.[5]

How are scientists able to estimate the concentrations of these gases in the atmosphere for thousands of years in the past? Ice cores bored in Greenland and Antarctica provide estimates of both temperature and atmospheric greenhouse gases going back hundreds of thousands of years. So far, Antarctic ice cores have yielded a continuous record of the past 740,000 years.[6] Variations in ice density associated with seasonal snowfall patterns provide a way to determine the age of specific points in some ice cores. By measuring the ratio of the hydrogen isotope deuterium (D) to hydrogen in the ice, scientists can calculate a proxy for the temperature at the time each layer of ice formed. By analyzing air bubbles trapped in this ancient ice, scientists can even measure the composition of the Earth's past atmosphere. The result of such an ice core analysis, shown in figure 1.5, gives dramatic evidence that temperature (measured by variations in deuterium; D) and greenhouse gas concentrations, particularly carbon dioxide,

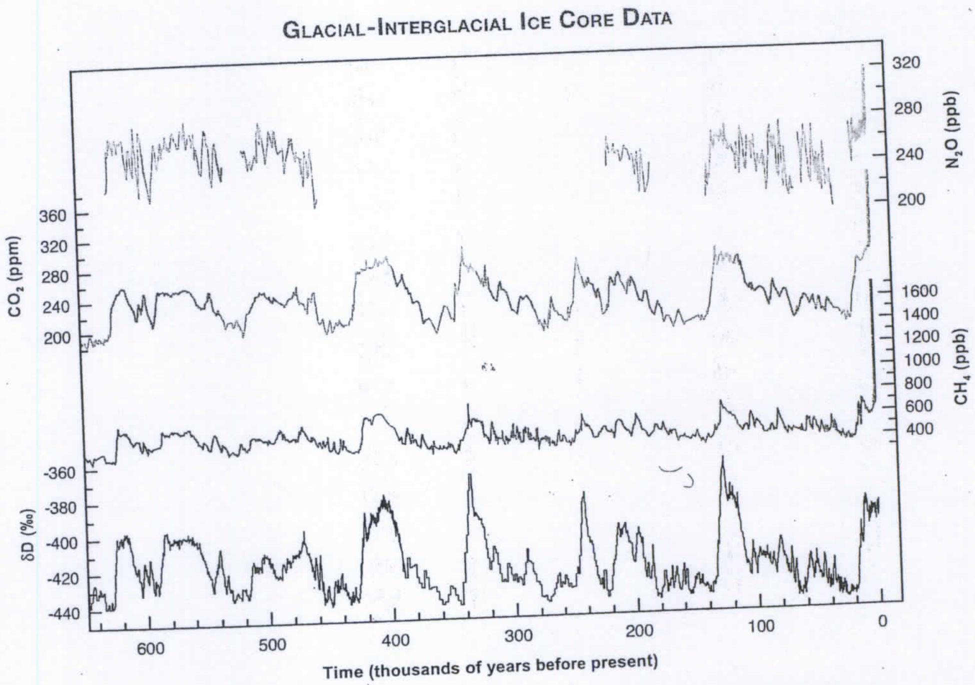

FIGURE 1.5. Variations of deuterium (δD; bottom line) in Antarctic ice core records, a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases carbon dioxide (CO_2; line second from top), methane (CH_4; line second from bottom), nitrous oxide (N_2O; top lines) in air trapped within these ice cores and from recent atmospheric measurements. Data cover 650,000 years, and the shaded bands indicate previous interglacial warm periods.

are correlated over the long term. Although greenhouse gases are not the sole trigger for climate change historically—other factors like variations in the Earth's orbit are likely to initiate and end ice ages—greenhouse gases amplify processes that accelerate ice age formation and eventual deglaciation. The data support the mechanistic understanding of the role of greenhouse gases in climate changes and their ability to cause current and future climate changes as human activities increase atmospheric greenhouse gas concentrations.

The maximum CO_2 concentration in the ice core record of the past 650,000 years is less than 300 ppm. The present-day concentration of around 380 ppm is far above anything the Earth has seen, probably, for millions of years. Figure 1.5 shows the recent rise in CO_2 and other greenhouse gases relative to the rest of the ice core data. Clearly, the anthropogenic increase in CO_2 concentration is unprecedented in both its size and its rapidity over this time period. We have made truly dramatic changes in the Earth's atmosphere over the past century or so, and we are already observing impacts of climate change around the world that will continue to grow. To begin to predict the extent of these changes, we must examine *all* of the important influences human activities have on the climate system.

Greenhouse Gases and Radiative Forcing

Climatologists characterize the effect of a given atmospheric constituent by its radiative forcing, the rate at which it alters absorbed solar or outgoing infrared energy. Water vapor is the most important greenhouse gas, but is not directly influenced much by human activities—only indirectly as a feedback process amplifying warming from the anthropogenic greenhouse gases. Carbon dioxide is the most important of the anthropogenic greenhouse gases, but other gases play a significant role, too. On a molecule-to-molecule basis, most other greenhouse gases are far more potent absorbers of infrared radiation than is CO_2, but they are released in much smaller quantities so their overall effect on climate is smaller. The second most prevalent anthropogenic greenhouse gas is methane. One methane molecule is roughly thirty times more effective at absorbing infrared than is one CO_2 molecule. Although CO_2 concentration increases tend to persist in the atmosphere for centuries or longer, methane typically disappears in decades, making its warming potential relative to that of CO_2 lower on longer timescales. Currently, the radiative forcing from anthropogenic methane is slightly less than one-third that of CO_2.

Other anthropogenic greenhouse gases include nitrous oxide and gases solely created through industrial processes, such as halocarbons used in refrigeration. Halocarbons include chlorofluorocarbons (CFCs), which are also the leading cause of stratospheric ozone depletion. Newer halocarbons do not cause severe ozone depletion but are still powerful greenhouse gases. They are hundreds to thousands of times more potent than carbon dioxide, molecule to molecule, and remain in the atmosphere for centuries to millennia, but appear in much lower concentrations than carbon dioxide and methane. Together, nitrous oxide and halocarbons account for approximately the same level of radiative forcing as methane. A number of other trace gases contribute a small amount of additional forcing. All the gases mentioned so far are well mixed, meaning that they last long enough to be distributed in roughly even concentrations throughout the troposphere, the lowest 10 kilometers of the atmosphere.

Finally, ozone (O_3), familiar because of the "ozone hole" and its depletion by anthropogenic CFCs, is also a greenhouse gas. Ozone in the troposphere near the surface is a potent component of smog, resulting largely from motor vehicle emissions. Tropospheric ozone contributes about one-fourth the radiative forcing of CO_2, although unlike the well-mixed gases, tropospheric ozone tends to be limited to industrialized regions, and it is of great concern for health effects as well as climatic influences.

The cooling of the stratosphere from added greenhouse gases has an effect on ozone, both by temperature-dependent atmospheric chemistry, which might slightly increase ozone levels in the tropical stratosphere, and by cooling of the polar stratosphere, which causes more high-altitude clouds that increase ozone destruction. Thus, there are many processes around the globe leading to climate and ozone changes arising from increasing the concentrations of greenhouse gases in the atmosphere above their natural levels.

Aerosols

Fuel combustion, and to a lesser extent agricultural and other industrial processes, produce emissions that create particulate matter. Coal-fired power plants burning high-sulfur coal, in particular, emit gases that become sulfate aerosols and reflect incoming solar energy, producing a cooling effect. Natural aerosols that produce a cooling effect are also created during volcanic eruptions and the evaporation of seawater, as well as from emissions of hydrocarbons in forested areas like the Great Smoky Mountains—hazes that are largely from biological emissions. Conversely, diesel engines and some biomass burning produce black aerosols such as soot, which absorb the sun's energy and, depending on circumstances, can warm the climate.

Aerosol particles also affect radiative forcing indirectly. For example, they act as "seeds" for the condensation of water droplets to form clouds, affecting the color, size, and number of cloud droplets, and, in aggregate, likely offset some greenhouse warming. The IPCC estimates that the negative radiative forcing resulting directly from all anthropogenic aerosols (e.g., aerosol hazes) offsets about one-third of the positive forcing from greenhouse gases, with indirect effects (e.g., the change in cloud optical properties resulting from pollutant aerosols) offsetting, in aggregate, roughly another third.[7] However, there is considerable uncertainty regarding these figures (especially the indirect effects), which may be much larger or much smaller than these central estimates, although still likely to be a net negative forcing. Unfortunately, the uncertainty in aerosol radiative forcing complicates the assessment of "climate sensitivity": the amount the Earth's surface warms for a given increase in forcing—typically a doubling of CO_2 over pre-industrial levels. The climate sensitivity is an important parameter in projecting future climate change.

Solar Variability

Another important influence on the climate system not affected by human activities is the variation in the sun's energy output. Variations caused by the twenty-two-year sunspot cycle are typically estimated to amount to only about 0.1 percent of solar output and are too small and occur too rapidly to explain a significant climatic effect like the late-twentieth-century warming in figure 1.2. However, long-term solar variations, either from variability in the sun itself or from changes in the Earth's orbit and tilt, have substantially affected the Earth's climate over tens of thousands of years. Accurate, satellite-based measurements of solar output are available for only a few decades. To estimate past variations in solar activity, scientists use proxies such as the level of the isotope beryllium-10 in ice cores. Beryllium-10 is generated by cosmic rays entering the atmosphere, and its level in ice goes down when the sun is active and the "solar wind" of energetic electrons and protons repels more of these cosmic rays, and vice versa.

The IPCC estimates that current solar forcing is equivalent to about one-tenth of the forcing from CO_2, which contributes somewhat to observed global climate change but is far below what is needed to fully account for the warming of recent decades. There are many hypotheses suggesting that various solar effects have generated climate change, but none are considered likely explanations of the recent climate warming.[8]

Radiative Forcing: The Overall Effect

Figure 1.6 summarizes our current knowledge of radiative forcing caused by green-

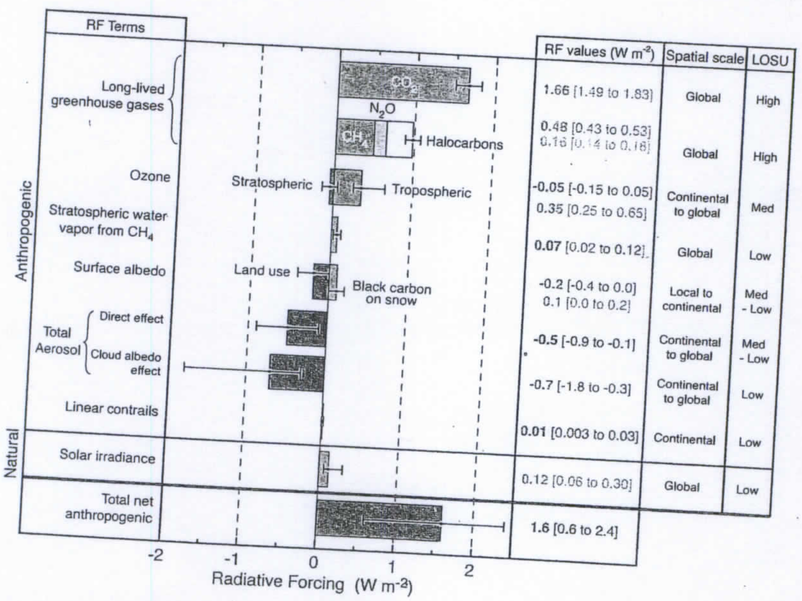

Figure 1.6. Global-average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and other important processes and components. The total net anthropogenic RF is also shown, which requires combining uncertainty estimates from the component terms and cannot be obtained by simple addition. For each, the bracketed range represents a 90 percent confidence interval (5 percent likelihood that the value could be above or below the range). Typical geographical extent (spatial scale) of the RF and the Working Group I authors' assessed level of scientific understanding (LOSU) are also reported. Volcanic aerosols contribute an additional natural forcing but are not included in this figure due to their episodic nature.

house gases, aerosols, land-use changes, solar variability, and other effects since the start of the industrial era.[9] The bottom bar presents an estimate of the total net current anthropogenic forcing. An important point to remember is that the individual forcings in the top panel have different levels of persistence and uncertainty. For example, different greenhouse gases remain in the atmosphere for different periods, as discussed previously. Therefore, the total net forcing is not a simple sum of the individual components. Comparing the top (CO_2) and bottom (total) forcing bars in figure 1.6, scientists estimate that total current forcing is roughly equal to the positive forcing from carbon dioxide.

Feedback Effects

Knowing the radiative forcing caused by changes in atmospheric constituents would be sufficient to project future climate, if there were no additional climatic effects beyond the direct change in energy balance. But a change in climate caused by simple forcing can have significant effects on atmospheric, geological, oceanographic, biological, chemical, and even social processes. These effects, in turn, can further change the climate. If that additional change is in the same direction as its initial cause, then the effect is called a positive or amplifying feedback. If that additional change is in the opposite direction, then it is a negative or dampening feedback. In reality, numerous feedback effects complicate the assessment of climate change. Here we list just a few feedback processes to give a sense of their variety and complexity.

Albedo is a planet's reflectance of solar radiation. The Earth's albedo is about 0.31, meaning that 31 percent of solar radiation is reflected back to space. A decrease in that number means that more radiation is absorbed. As the amount of radiation absorbed increases, global temperature also increases. One consequence of rising temperatures is the melting of snow and ice, which can already be observed in many parts of the world in the form of melting and receding mountain glaciers and decreasing snowpacks. Such melting eliminates a highly reflective surface and exposes the darker land or water beneath the ice. The result is a decreased albedo, increased solar energy absorption, and additional warming. This is a positive feedback.

Rising temperature also results in increased evaporation of water from the oceans into the atmosphere. Because water vapor is itself a greenhouse gas, this effect results in still more warming and is thus a positive feedback. Most assessments suggest that the overall effect of increased water vapor with global warming is a positive feedback that causes a temperature increase some 50 percent higher than would occur in the absence of this feedback mechanism.[10] But increased water vapor in the atmosphere can also mean more widespread cloudiness. More cloudy areas raise the Earth's albedo by reflecting more incoming solar radiation. This reflection results in less energy absorbed by the Earth-atmosphere system, a negative feedback if the increased cloud amount was caused by some positive forcing. On the other hand, more clouds mean greater absorption of outgoing infrared radiation from the Earth's surface. Furthermore, more evaporation or surface heating could mean increases in cloud top heights that would add to the greenhouse effect. Both of the latter processes are positive feedbacks. The net effect of increasing cloud amount depends on latitude and season, but averaged annually over the globe it is often estimated to be a positive feedback.[11] However, uncertainty in the *net* cloud feedback—including changing cloud amount, top height, and microphysical properties like number, color, or size of droplets—makes it difficult to precisely estimate how sensitive the climate is to increasing greenhouse gas concentrations (see chapter 15).[12]

As mentioned above, huge amounts of carbon are continuously cycled among the atmosphere, ocean, land, and terrestrial biosphere as part of the global carbon cycle. In fact, a significant fraction of anthropogenic emissions are removed from the atmosphere by oceanic and terrestrial uptake. Increasing atmospheric greenhouse gas concentrations influence these processes in many ways.

For example, CO_2 dissolves in water. As CO_2 in the atmosphere increases, more CO_2 dissolves into surface waters, which is a negative feedback on CO_2 concentrations in the climate system. Some of this oceanic dissolved CO_2 is taken up by phytoplankton (tiny plants) and other organisms that are capable of photosynthesizing and thus converting it to organic material. Zooplankton (small marine animals) graze on the phytoplankton. When these phytoplankton and zooplankton die, their bodies sink, along with other organic matter, transporting the carbon to the deep ocean. Much of the carbon is redissolved along the way, but some reaches the ocean floor and is buried, becoming sediment. This small fraction becomes very significant to the carbon cycle over long timescales. Warmer water can hold less CO_2 than colder water, so as temperature increases, the uptake of atmospheric CO_2 will slow, which is a positive feedback. Scientists estimate that oceanic processes currently take up about one-fourth of CO_2 from fossil fuel burning, but this uptake may slow in the future as warming inhibits overturning of surface waters with the deep ocean, and as ocean acidification and increasing temperature reduce the rate of CO_2 uptake (see chapter 5).

In the terrestrial biosphere, increased atmospheric CO_2 stimulates plant growth, and plants in turn remove CO_2 from the atmosphere, which is a negative feedback. On the other hand, warmer soil temperatures stimulate microbial action that releases CO_2 from the decomposition of dead organic matter, which is a positive feedback. Scientists estimate that terrestrial processes currently take up about one-tenth of CO_2 emissions from fossil fuel burning, the so-called land sink. This represents a larger sink from plant growth partially offset by emissions from land-use change, such as deforestation. What will happen to this sink in the future is highly uncertain. Several studies simulating future climate indicate that this sink may become a source of additional emissions later this century even if deforestation decreases, primarily due to increased release of carbon from soils as temperatures warm beyond a degree or two Celsius.[13]

There are even social feedbacks. For example, rising temperature causes more people to install and use air conditioners. If the resulting increase in electrical consumption resulted in more fossil fuel-generated atmospheric CO_2, that would be another positive feedback. Increasing temperatures and climate impacts, combined with assessments of future risks, may encourage more stringent policies to reduce emissions, which will in turn reduce further intensification of those impacts, a negative social feedback also known as climate mitigation policy.

Accounting for all significant feedback effects entails not only identifying important feedback mechanisms, but also developing a quantitative understanding of how those mechanisms work. Such understanding often includes research at the boundaries of

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disciplines, including meteorology, atmospheric chemistry, oceanography, biology, and geology; social sciences such economics and sociology; and research on technological development.

Climate Models

Uncertainty in future greenhouse gas emissions and in scientific understanding of the response of the climate system to their influence makes projecting future climate change a complex task. The most sophisticated tools we have are global models of the climate system. Not only can they reproduce global temperature records, as shown in figure 1.3, but the best model results reproduce, although not completely, the detailed geographic patterns of temperature, precipitation, and other climatic variables seen on a regional scale, and can project changes in those patterns given scenarios for future greenhouse gas emissions.

A climate model is a set of mathematical statements describing physical, biological, and chemical processes that determine climate. What must go into a climate model depends on what one wants to learn from it. A few simple equations can give a reasonable range of estimates of the average global warming in response to specified greenhouse forcings. Our estimate above that the Earth's global average temperature in the absence of the greenhouse effect would be colder by about 33 degrees Celsius was based on a simple climate model. In that case, the Earth's surface is treated as a single point, with a simple height-varying atmosphere and no distinction between land and oceans. Simple models have the advantage that their predictions are easily understood on the basis of well-known physical laws. Furthermore, they produce results quickly and can, therefore, be used to test a wide range of assumptions by changing parameters of the model. More advanced are "multibox" models that treat land, ocean, and atmosphere as separate "boxes" and include flows of energy and matter between these boxes. More sophisticated multibox models may break the atmosphere and ocean into several layers or the Earth into several latitude zones.

Most sophisticated are the complex computer models known as general circulation models (GCMs). Such detailed models can only be run effectively on a limited number of supercomputers around the world. These divide the Earth's surface into a grid that can represent with reasonable accuracy the actual shape of the Earth's land masses and, to a lesser extent, mountains. The atmosphere above and ocean below each surface grid cell are further divided into layers, making the basic unit of the model a small, three-dimensional cell. Properties such as temperature, pressure, and humidity are averaged within each cell. Equations based in physics, chemistry, and biology regulate the various quantities within a cell, and other equations describe the transfer of energy and matter between adjacent cells. The newest models also include processes such as the cycling of carbon between the atmosphere, land, and ocean, the response of the Earth's vegetation to changing conditions and its feedbacks to the climate system, atmospheric chemistry, and the functioning of the cryosphere. Figure 1.7, panel A, displays the typical geographic resolution of the grid representing northern Europe at the time of each of the four IPCC assessment reports and the improvement in resolution (i.e., grid-box size) over this period. Panel B displays the progression in climate models since the 1970s in terms of the processes and com-

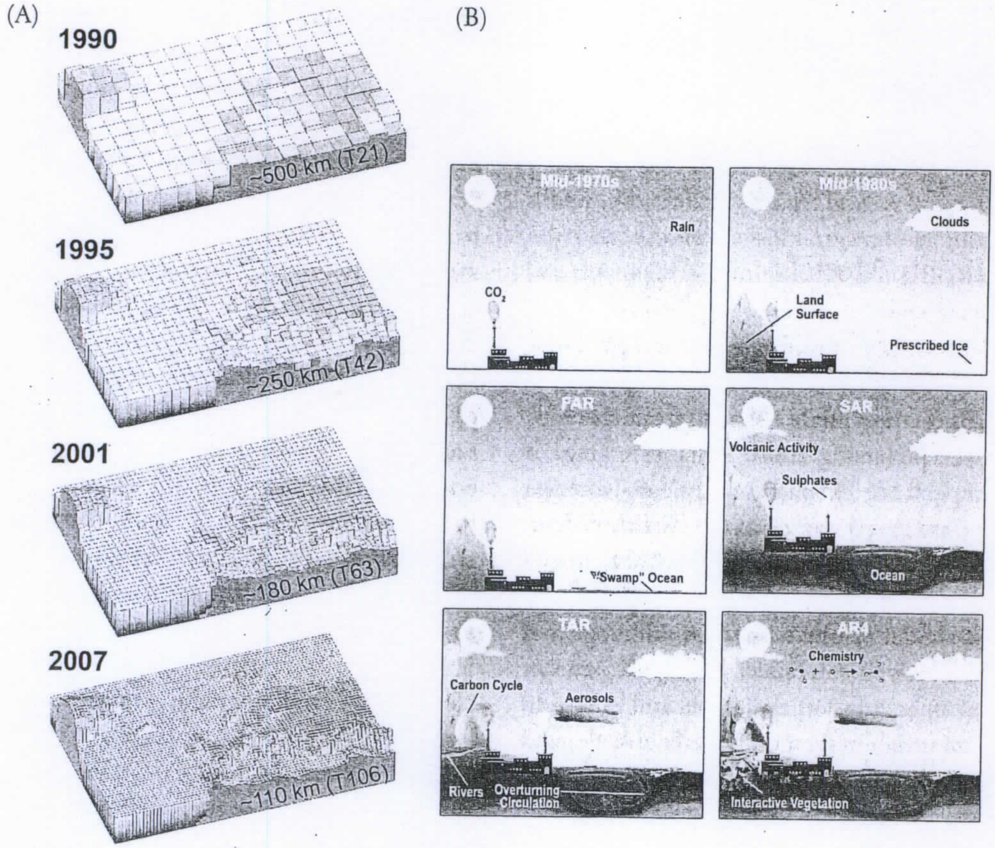

FIGURE 1.7. Panel A: Geographic resolution of GCMs at the time of each of the IPCC assessment reports. Vertical resolution in both atmosphere and ocean models is not shown, but has increased as well, beginning typically with a single-layer "slab" ocean and ten atmospheric layers in 1990 and progressing to about thirty levels in both atmosphere and ocean in 2007. Panel B: The complexity of climate models has increased during the last few decades. The series of pictures displays different features of the modeled world and when they were incorporated. Source: Intergovernmental Panel on Climate Change (IPCC), 2007(a), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon et al. (eds.), Cambridge University Press: Cambridge, United Kingdom.

ponents of the climate system that GCMs incorporate.[14]

Even with the rapid expansion of computational power, the best global climate models are currently limited to a geographic grid-box resolution of roughly 100 kilometers horizontally and 1 kilometer vertically. But climatically important phenomena occur on smaller scales, such as clouds or the substantial thermal differences between cities and surrounding areas. Because all physical, chemical, and biological properties are averaged over a single grid cell, it is impossible to represent these phenomena *explicitly* within a model. But they can be treated *implicitly* with what is called a parametric representation, or "para-

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meterization." A parameterization connects small-scale processes to grid-box averages with semi-empirical rules designed to capture the major interactions between explicitly modeled grid-scale variables and sub-grid-scale processes. For example, a grid cell half covered by scattered clouds might be parameterized as a uniform blockage of somewhat less than half the incoming sunlight. Such an approximation manages not to ignore clouds altogether but doesn't quite handle them correctly. One can imagine that the effects of full sunlight penetrating to the ground in some parts of a grid box while other parts are in full shade might be different from those of a uniform light overcast, even with the same total energy reaching the ground averaged over the grid box.[15]

Model Validation

How can modelers be confident in their model results? How do they know that they have taken into account all climatologically significant processes and that they have satisfactorily parameterized processes whose scales are smaller than their models' grid cells? The answer lies in a variety of model validation techniques, most of which attempt to reproduce known climatic conditions in response to known forcings.

Major volcanic eruptions inject enough dust into the stratosphere to exert a global cooling influence that lasts several years. Such eruptions typically occur once a decade or so, and they constitute natural experiments that can be used to test climate models. The climatic effects of the largest recent major eruption, Mount Pinatubo in 1991, were forecast by a number of climate modeling groups to cool the planet by several tenths of a degree Celsius for a few years. That is indeed what happened.

Seasonality provides another natural experiment for testing climate models. Winter predictably follows summer, averaging some 15 degrees Celsius colder than summer in the northern hemisphere and 5 degrees Celsius colder in the southern hemisphere (the southern hemisphere variation is smaller because a much larger portion of that hemisphere is water, with a high heat capacity that moderates seasonal temperature variations). Climate models do an excellent job of reproducing the timing and magnitude of the seasonal temperature variations, although the absolute temperatures themselves may not be completely accurate.

Still another way to gain confidence in a model's future climate projections is to model past climates. Starting in 1860 with known climatic conditions, for example, can the model reproduce a reasonable simulation of the temperatures observed during the twentieth century? The "experiments" of figure 1.3 discussed previously provide clear evidence that the answer is "mostly yes" and also help modelers understand what physical processes are significant in determining past climate trends.

Climate models certainly have room for improvement. For example, models are less accurate in representing climatic variations involving precipitation and other aspects of the hydrologic cycle. While temperature changes are driven by large-scale forcing such as greenhouse gas heat-trapping or continental-scale aerosol cooling, precipitation is influenced by complex local/regional processes like the nature of the land surface, proximity to topographical features (e.g., mountains), and temperature differences across the region. All of those interacting smaller-scale processes and drivers are more difficult to include accurately in models. Nevertheless, today's climate models can reproduce recognizable simulations of regional patterns of temperature, precipitation, and other climatic variables. These pattern-based comparisons of models and reality provide further confirmation of the models' broad-scale validity. No one model validation experiment alone is enough to give us high confidence in future climate projections. But considered together, results from the wide range of experiments probing the validity of climate models give considerable confidence that these models are treating the essential climate-determining processes with reasonable accuracy—certainly for temperature trends at continental scales, and with some skills for regional trends and/or precipitation changes in certain regions like high latitude continents and Mediterranean climates of the subtropics.[16] Furthermore, researchers have linked grid-box-scale changes in temperature with observed changes in the lifecycles of plants and animals during the last fifty years (see chapter 3).[17]

Conclusion

We have given a thumbnail sketch of the science of global climate change. The greenhouse effect and its intensification by human-induced emissions of greenhouse gases are well understood and solidly grounded in basic science. Likewise, observed warming is now unequivocal, and many impacts of that warming can already be observed around the world. Nevertheless, the future effects of climate change are characterized by deep uncertainty, compounded by the global scale of the problem and the fact that climate change is not just a scientific topic but also a matter of public and political debate. There are two general sources of uncertainty in projecting future climate change: what we do and how the natural climate system responds. Policy decisions can strongly influence the first source of uncertainty (future emissions), but will have little influence on the second source (climate response to emissions). We cannot know precisely what the severity of impacts will be for a specific trajectory for future emissions, but we can confidently say that the severity will be reduced if emissions are reduced. In very general terms, climate policy is about managing risk: assessing the potential impacts of climate change, judging how likely it is that various impacts will occur, and determining how our policy choices will affect those risks.

Notes

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