to the residents of Novosibirsk, with a suggestion that they start growing palm trees

1

Why the Earth Is Getting Warmer

Just a tiny little bit

Carbon dioxide (CO_2) is a non-toxic gas. It is contained in every carbonated drink, and its sparkle feels refreshing. But it also strikes fear in us, because ever-larger amounts of it are being released into the atmosphere, accelerating the greenhouse effect. Akin to the glass panels in a greenhouse, CO_2 traps sunlight and thereby warms the planet.

Burning the carbon contained in oil, coal, natural gas, wood, and other organic matter produces carbon dioxide. The fats, carbohydrates, and proteins burned chemically by living organisms also contain carbon.

It is striking how little carbon dioxide the atmosphere contains. It accounts for barely 0.038 percent of the atmosphere. Chemists refer to this as 380 ppm, with ppm standing for parts per million. Before industrialization, the CO_2 concentration was 280 ppm. And, by the way, any gas spreads out in the atmosphere in such a way that its molecules are separated equally from each other when the air pressure is the same. The volume ratio thus always corresponds to the ratio of the number of molecules.[1] Owing to the differing weight of the respective molecules, however, the weight ratios do not correspond to the volume ratios. CO_2 is a pretty heavy gas, and without constant movement of the air it would concentrate near the ground.

Oxygen and nitrogen constitute 97 percent of the atmosphere. Oxygen accounts for 21 percent; nitrogen accounts for 76 percent. The rest consists of approximately 2.5 percent water vapor and numerous trace gases, of which CO_2, at 380 ppm, is the most important for climate. The second most important is methane (produced by the decay of plant matter in the absence of oxygen, for instance in the stomachs of cattle); it accounts for 1.8 ppm. Greenhouse gases, strictly defined, include carbon dioxide, methane, nitrous oxide, and other trace gases. A broader definition includes water vapor.

Water vapor plays a very significant role in the greenhouse effect. It is usually present as an invisible, wholly diluted gas, but it can quickly condense at lower pressures or temperatures and turn into clouds, rain, or snow. Its concentration varies greatly. The greenhouse effect occurs only when water vapor is in its uncondensed, invisible form. As a rule, 96 percent of the water in the atmosphere consists of water vapor. The remaining 4 percent is in the form of water droplets and ice crystals in clouds, rain, and fresh snow.[2]

Greenhouse gases are, in fact, not a problem but a boon for mankind. As is often the case, it all depends on the right dose. If there were no strictly defined greenhouse gases and no water as vapor or clouds in the air, the atmosphere would consist exclusively of oxygen and nitrogen, which it nearly does anyway, and the planet would be barely inhabitable, because the average temperature at ground level would be –6°C (21°F). (It would be much colder if there were water in the form of vapor and clouds in the air but none of the strictly defined greenhouse gases, as the cloud cover would be so thick that little sunshine would reach the ground. This will be explained below.) At present, the average temperature at ground level is 14.5°C (58.1°F), whereas in pre-industrial times it was 13.5°C (56°F). Therefore, the greenhouse gases, including water vapor, caused an increase in the ambient temperature of about 20°C (36°F).[3]

In this light, we can count ourselves fortunate that greenhouse gases exist at all. It was these gases that made life as we know it possible. A temperature of 14.5ºC doesn't sound very comfortable, but in fact it is quite acceptable if one considers that it is an average that encompasses the polar caps and the tropics, winter and summer, and day and night. This is a temperature at which both people and nature feel comfortable, because evolution made us for it. In the past million years of evolution, average temperatures were around 11°C (52°F), rising by 4°C (7.2°F) during interglacial warm periods and falling by 2°C (3.6°F) during ice ages. Plants and animals can cope with changes of this magnitude because they can move back and forth between cold and warm regions.

During the last ice age, which ended 18,000 years ago, the average temperature was about 5.5°C (10°F) lower than today's. No one lived in Europe north of the Alps, as practically the entire region was buried under an ice layer.[4] In Germany, which now has an average temperature of 9°C (48°F), the average temperature was approximately –4°C (25°F).[5] However, our ancestors found temperate areas in Africa, in India, in Australia, and around the Mediterranean. The African tropics, which now boast an average temperature of 26°C (79°F), had an average temperature of about 21°C (70°F) back then—a level that nowadays can be found in northern Egypt, Texas, or southern Italy. Southern Italy then had an average temperature similar to Germany's today—from 8ºC to 10ºC lower than today's average.[6]

But a boon can turn into a bane if the concentration of greenhouse gases increases as a result of mankind's activities, because the climate reacts with extraordinary sensitivity to such gases. If the current concentration (0.038 percent), plus water vapor, can raise temperatures by 20°C (36°F), an uncontrolled increase can quickly turn into a calamity. God preserve us from conditions such as those on Venus, whose atmosphere consists mainly of carbon dioxide and water vapor. The greenhouse effect there has brought about temperatures of 525°C (977°F), rendering neither life nor love possible. Lovers are advised to keep their distance from Venus.

The greenhouse effect

Behind the public pronouncements on the greenhouse effect lie sound theories and vast records of measurements and observations. As these are shared by practically every leading climate scientist, there can be little doubt about the greenhouse basics, despite some irritating public debates in recent years. The first studies of the greenhouse effect were conducted in the nineteenth century. A veritable flood of scientific publications on the subject are now available.[7] The recognized authority on interpretation of the data and application of the associated theories is the Intergovernmental Panel on Climate Change (IPCC), a network of about 2,500 researchers that monitors climate change and publishes regularly updated reports on the subject.[8]

Climate research starts from the fact that a gas that consists of at least three atoms acts as a filter, absorbing certain wavelengths in the infrared, growing warm, and passing this warmth on to the gases surrounding it. The energy contained in the sunlight radiated by the Earth back to space, mainly in infrared frequencies, plays a major role in this. Three-atom greenhouse gases include carbon dioxide (CO_2), water vapor (H_2O), nitrous oxide (N_2O), and ozone (O_3). Methane has the chemical formula CH_4, which means it consists of five atoms. The gases grouped under the name "chlorofluorocarbons" (abbreviated CFCs) have at least six atoms. Akin to a color filter that absorbs a certain spectrum and so tints everything in a certain hue, the greenhouse gases absorb certain spectral colors. Oxygen (O_2) and nitrogen (N_2) don't produce any greenhouse effect, as each of their molecules contains only two atoms.

Sunlight has a wide color spectrum that contains particularly high levels of energy in the shorter (blue) wavelengths. It reaches the surface of the Earth practically unhindered, warms it, and turns into infrared light, which is then reflected by the Earth. We can't see infrared light, but we can feel its warmth. The police are very fond of shooting pictures in infrared, and we can do that ourselves in order to find out where warmth leaks out of our houses. A significant portion of the infrared light reflected by the Earth is absorbed by the greenhouse gases, converted into heat, and thus prevented from being expelled into space. This keeps our planet warm.

It keeps it warm, but it doesn't make it ever warmer. In theory, the Earth has a stable average temperature whose level depends on greenhouse-gas concentrations and other factors. When we say that the temperature is stable, we don't mean that it is constant; we mean that after an external disturbance, such as a change in solar radiation or a displacement of the continents, it reverts to a new equilibrium. An egg carried in a spoon is in a stable position. Although it rocks to and fro, it returns to stillness once the person carrying the spoon stops moving. If, however, one places the egg on the back of the spoon, it will be in an unstable position, and the tiniest movement will send it tumbling down. The temperature of our planet will not swing explosively if a change in solar radiation occurs, but it will experience minor swings that dampen down with time, tending toward an equilibrium. Fortunately, temperature changes caused by external factors don't build up over time. If the temperature were not stable, life would not be possible on our planet, because the many disturbances during its history would have turned it alternatively into a frozen waste and then a stifling desert.

The temperature remains stable because the more energy the Earth absorbs, the more it radiates back into space. If external factors make the planet warmer than what corresponds to its stable temperature, it radiates more energy into space and so the increase in temperature is slowed. Conversely, when an external factor makes it cooler, the planet radiates less energy than it receives from the sun, which slows the decline of temperature. It is like a light bulb. The current flowing into it doesn't make the filament shine ever more brightly; its brightness is determined by an equilibrium between the amount of energy being dissipated as light and the amount of electrical energy flowing in.

Averaging out all its regions, winter and summer, day and night, the Earth, including its enveloping atmosphere, receives an amount of energy amounting to 343 watts per square meter (32 watts per square foot). It must then be warm enough to radiate exactly this amount of energy back into space. If the atmosphere contained only oxygen and nitrogen, and neither water vapor nor clouds, nor carbon dioxide, nor any of the other greenhouse gases, the air and the surface would reflect 55 watts back to space immediately, so that 288 watts would remain to warm the planet's surface and its air. The temperature on the surface would then stabilize at a level at which the heat radiated back to space would equate to 288 watts per square meter. Without strictly defined greenhouse gases, and without water vapor, this temperature would amount to –6°C (21.2°F).

The proportion of water in the atmosphere can hardly be disregarded in a comparative scenario, though, because it depends on the temperature that drives the evaporation of the ocean's waters. Moreover, account has to be taken of the fact that lower temperatures lead to more condensation of water vapor in the atmosphere, which diminishes the amount of solar radiation reaching the surface. In the absence of strictly defined greenhouse gases, but with water in the atmosphere, the average temperature would be –18°C (– 0.4°F).[9] Not only would our planet be as cold as Siberia; the cloud cover would let hardly a sunbeam through.

The nearly 32°C (58°F) temperature increase from –18°C to +13.5°C that makes our planet inhabitable comes mainly from the fact that carbon dioxide and the other narrowly defined greenhouse gases trap some of the radiated heat. Figure 1.1 schematizes this relationship. The higher temperature leads to increased evaporation from the oceans, and with the higher water vapor content in the atmosphere a further greenhouse effect comes into play. With the increased warmth, there is less cloud formation, which in turn accelerates warming. Though the clouds block some of the radiated heat, the fact that they reflect sunlight exerts a larger effect. All in all, during the pre-industrial period, with the greenhouse gases present then, a temperature of +13.5°C (56.3°F) was necessary to radiate back into space exactly the 343 watts per square meter that the planet received from the sun.

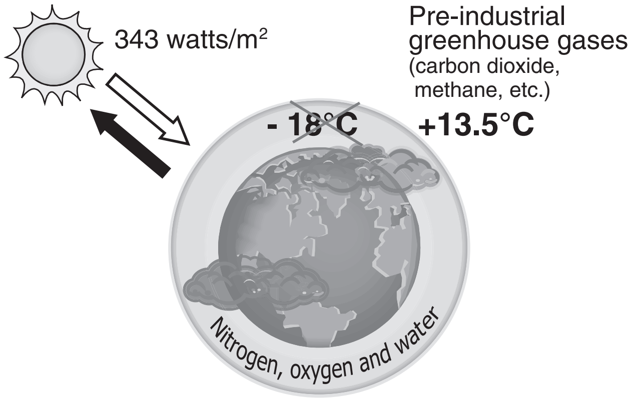

Figure 1.1
Warming the Earth.

Why it all comes down to carbon dioxide

Greenhouse gases aren't all alike. Each has its peculiarities, and these must be understood in order to ascertain their meaning for our climate.

Water vapor is the most important greenhouse gas. Though its contribution per molecule to the greenhouse effect is equal to only 4 percent of the contribution of carbon dioxide, there is so much water vapor in the atmosphere that it accounts for about 65 percent of the total effect. With about 2.5 percent per volume (that is, 25,000 ppm), it is by far the most abundant climate-relevant gas in the atmosphere.[10]

But given that water vapor concentration in the atmosphere is endogenously determined by the Earth's temperature, water vapor usually isn't included among the greenhouse gases. This gives rise to the distinction between strictly and broadly defined greenhouse gases mentioned above. Though water vapor has an enormously important feedback or self-reinforcement effect in greenhouse mechanics, it isn't an autonomous determining factor that can be changed by the hand of man, other than through temperature itself.

This is important in view of the common assertion that the influence of carbon dioxide is irrelevant relative to the overwhelming importance of water vapor. Instead of focusing on CO_2, the argument goes, we should pay attention to the fact that enormous amounts of water vapor are expelled into the atmosphere from the cooling towers of power plants and through the burning of hydrocarbons such as coal, natural gas, and oil. Furthermore, attention ought to be paid to the fact that a hydrogen-based economy, which would release significant amounts of water vapor into the atmosphere, would warm the planet even more. These assertions ignore the fact that the proportion of water vapor in the atmosphere regulates itself continuously through the weather. Water vapor is released from the oceans, condenses, rains down again within 8 to 10 days, and is brought back to the sea by the rivers.[11] How much of this constantly circulating water vapor remains in the atmosphere and contributes to the greenhouse effect depends on the temperature of the air. The warmer the air, the more water vapor it can store. You can see it any morning: dew evaporates as the air temperature increases. Any amount of additional water that human activities pump into the air will quickly rain down again and thus can't contribute to the greenhouse effect.

Carbon dioxide, in contrast, plays a central role in the influence that human activities are exerting on the climate. Though it ranks second to water vapor as a greenhouse gas and accounts for about 60 percent of the third not accounted for by water vapor (see table 1.1), CO_2 is incomparably more important than water vapor in explaining climate change, because its content in the atmosphere isn't determined solely by natural processes but rather keeps increasing as a result of human activities.

Carbon dioxide readily binds with water vapor, forming carbonic acid, and gets washed into the oceans when it rains. Waves then release it back into the atmosphere, in a fashion similar to the bubbling away of carbon dioxide when you shake a soda bottle. However, this exchange process has little similarity to the water cycle, as the amount of CO_2 that the atmosphere can absorb isn't limited by natural forces; it can be increased almost indefinitely by human activity. What is limited is the capacity of the oceans' upper layers to absorb it. As the concentration of CO_2 increases in these layers, which are responsible for the exchange between water and air, a larger amount of CO_2 will be released by the waves. Thus, only a limited amount of the CO_2 released by human activities can be absorbed by the seas; the rest accumulates in the atmosphere and in biomass.

As was noted above, water vapor gives rise to a feedback effect in climate because higher temperatures lead to more water vapor, which in turn increases the greenhouse effect. Carbon dioxide shows a similar reinforcing pattern. As the temperature of the oceans rises, their capacity to absorb CO_2 decreases. We know this phenomenon from the spraying that happens when we open a warm soda bottle. If external factors bring about a rise in the Earth's temperature, the seas release more carbon dioxide, increasing the concentration of this gas in the atmosphere and thus exacerbating the Earth's warming. We could call this the "fizzing effect." The fizzing effect—that is, the reduced capacity of the seas to absorb CO_2 in the presence of increasing temperatures—is the most important destabilizing factor for our climate.

Another destabilizing factor would be the thawing of the permafrost regions, most of which are in Siberia and Canada. Should this happen, a decay processes in those tundra regions would take place, releasing carbon dioxide and methane and thus accelerating the greenhouse effect. Fortunately, these destabilizing factors aren't strong enough to bring the planet's temperature to a tipping point. Since the stabilizing effect of higher amounts of infrared wavelengths being radiated back to space after an increase in temperature is significantly stronger, the resulting greenhouse effect would bring about a considerable increase in the planet's temperature but not an uncontrolled, runaway one.

Carbon dioxide is absorbed not only by the oceans but also by plants. If the atmosphere contains higher proportions of CO_2, some plants grow faster, as a nutrient relevant to their growth would be more abundantly available. On the other hand, the subsequent decay of those plants would release higher amounts of carbon dioxide as well. Still, more carbon dioxide will be absorbed than released, as the biomass stock in terms of plants and animals would increase. This would slow the pace at which temperature increases and thus act as a climate stabilizer. More vegetation can only slow the release of CO_2 into the atmosphere, however; it can't stem it. The vegetation effect is much too weak to prevent temperature increases, not least because high enough temperatures can also cause plants to die off.

Carbon dioxide is much more chemically stable than other greenhouse gases. It doesn't react with other gases in the air, and therefore it doesn't break down. It is being pumped into the atmosphere as a result of the burning of fossil fuels, adding to the stocks already there. This is the principal reason it plays such a significant role in concerns about our climate. Only when the carbon dioxide washed by rain into the oceans enters into a reaction with calcium, building calcium carbonate, and gradually sinks to deeper layers, can the stock of CO_2 in the atmosphere be reduced, but these processes, from our human perspective, are far too slow to pose a solution to climate change. The average time CO_2 emitted today would stay in the atmosphere ranges from 30,000 to 35,000 years.[12]

Other greenhouse gases

Another important greenhouse gas is methane (CH_4), with a concentration of 1.8 parts per million. Methane is a natural gas, most of which leaks out of underground deposits. But it also arises from the natural decay of organic matter. If oxygen is present in the decay process, CO_2 is produced. If decay occurs in the absence of oxygen, methane is produced. This is the case mainly in humus layers, but can also occur through fermentation in the stomachs of ruminants. Methane absorbs much more radiation per unit of weight than CO_2 does. Fortunately, it reacts with oxygen and decays into water and CO_2 in about 15 years on average. It continues to be damaging for our climate, but not as much as it was before decaying. For this reason, the usual practice is to measure its contribution to global warming not in terms of its current absorption of radiation but in terms of the total contribution that one kilogram of methane, in comparison to one kilogram of CO_2, makes to global warming over a certain span of time. Measured this way, methane's greenhouse effect per unit of weight amounts to 72 times that of CO_2 over 20 years, 25 times that of CO_2 over 100 years, and 8 times that of CO_2 over 500 years.[13] Per molecule, its greenhouse effect over 100 years amounts to 9 times that from CO_2. The last figure is important because it helps us understand the consequences of burning methane. Because burning one molecule of methane yields one molecule of CO_2 and two molecules of water, and because excess water is quickly removed from the atmosphere as rain, burning reduces methane's greenhouse effect over 100 years by about a factor of 9. For this reason, we should never allow methane to reach the atmosphere unburned. It is a pity that in drilling for oil the escaping gas is burned rather than put to profitable use, but burning it is better than pumping it into the atmosphere. Farmers must also be congratulated for turning organic waste into gas that they can use for heating, instead of just letting it rot away unattended.

Nitrous oxide (N_2O), with 0.3 ppm, ozone (O_3), with 0.015–0.050 ppm, and the CFCs, with 0.0009 ppm, also have some importance for climate.[14] Nitrous oxide is produced mostly through the use of fertilizers in agriculture. Ozone, which occurs naturally at altitudes of 20–40 kilometers (12–25 miles), forms a barrier against ultraviolet radiation. Ozone is also a major component of summer smog, which occurs at ground level mainly as a result of car exhaust's reacting to sunlight and which is quite unhealthy. Over 100 years, the greenhouse effect of a unit of weight of nitrous oxide amounts to 298 times that of CO_2, and that of a unit of weight of ozone amounts to as much as 2,000 times that of CO_2. But because their concentrations are low, these greenhouse gases account for only 13 percent (N_2O 4 percent; O_3 9 percent) of the anthropogenic (man-made) greenhouse effect.

Chlorofluorocarbons are somewhat more important. The term "chlorofluorocarbons" refers to a group of gases with comparatively complex chemical formulas that cause a great deal of damage in the atmosphere because they destroy the ozone layer that not only contributes to the greenhouse effect but also protects us from ultraviolet radiation from the sun. CFCs are synthetic gases; that is, they aren't found in nature. They were once used in spray cans and in refrigerators, from which they leaked out into the atmosphere. Since 1987, when their production was banned through the Montreal Protocol, the stocks of these gases in the atmosphere have been gradually decreasing, and the ozone holes over the poles are starting to close again. The proportion of one of these gases, CFC-11, reached its peak in 1993 and has been slowly decreasing ever since. No reduction in the concentration of CFC-12 can be detected yet, but since the early 1990s its rate of increase has diminished markedly.[15] The CFCs are important for climate change because relative to their size they produce an enormous greenhouse effect—between 5,000 and 10,000 times as strong per molecule, and up to 11 times as strong per unit of weight, as carbon dioxide's. Over the next 100 years, the CFCs already released into the atmosphere will account for about one-ninth of global warming.

Over 100 years, the current combined greenhouse gases, excluding carbon dioxide and water vapor, will produce a greenhouse effect equivalent to 50–70 ppm of carbon dioxide. That is why at present the "CO_2-equivalent" greenhouse-gas concentration, without water vapor, amounts to approximately 430–450 ppm.[16]

Table 1.1 provides an overview of the current sources of greenhouse gases. The first column gives the volume shares of the various gases in the atmosphere. The second column gives their average permanence in the air. The values range from two months for ozone to 35,000 years for CO_2. The third column gives the greenhouse effect of a kilogram (2.2 pounds) of the respective gas over the next 100 years relative to a

Table 1.1
The greenhouse gases (other than water vapor). Sources: C. D. Schönwiese, *Klimatologie*, second edition (Ulmer, 2003), p. 337; S. Solomon et al., *Climate Change 2007: The Physical Science Basis* (Cambridge University Press, 2007); L. K. Gohar and K. P. Shine, "Equivalent CO_2 and its use in understanding the climate effects of increased greenhouse gas concentrations," *Weather* 62 (2007): 307–311.

Greenhouse gas	Concentration today (ppm)	Average life (years)	Greenhouse potential per unit of weight over 100 years	CO_2 equivalent concentration today (ppm, 100 years)	Percentage of greenhouse effect (100 years)
Carbon dioxide (CO_2)	380	30,000–35,000	1	380	61%
Methane (CH_4)	1.8	15	25	26.3	15%
CFC	0.0009	100	1,810–10,900*	14.3	11%
Ozone (O_3)	0.015–0.05	0.16 (2 months)	<2,000	18.9	9%
Nitrous oxide (N_2O)	0.3	114	298	8.5	4%

*CFC-11, CFC-12, CFC-22

kilogram of CO_2. The fourth column gives the CO_2 equivalent in particles per million for the respective gases according to their current concentration in the atmosphere. This forms the basis for the calculation of their greenhouse effect over a period of 100 years. The last column, which gives the percentage share in the greenhouse effect of each gas, except water vapor, illustrates starkly why such overwhelming significance is attached to carbon dioxide in devising appropriate climate policies.

The human influence

Thanks to the many air samples from times past that nature has left us, we know fairly accurately how much the proportion of carbon dioxide in the atmosphere has changed since the Industrial Revolution. Such air samples are found in air bubbles trapped between rock layers and in the ice of glaciers and the polar caps. The deeper you drill, the older the sample.

The ice cores drilled on the Law Dome in East Antarctica give particularly good measurements.[17] They show that the concentration of CO_2 remained nearly constant at 280 ppm and began to increase sharply after the year 1800, rising to the present-day value of 380 ppm. There is no other explanation for this increase than industrialization. Burning fossil fuels—at first mostly coal, then, starting around the end of the nineteenth century, also oil—has left its traces on our planet. Natural gas, because of its lower consumption and its high content of hydrogen, has thus far played only a minor role. Clearing forests has played a role, however—see chapter 3.

Cement also has been of some importance, as its production releases large amounts of CO_2. When calcium carbonate, the raw material for cement, is heated, it produces lime and CO_2. This process is called calcination. The CO_2 released during calcination comes in addition to that released by the fuels used to fire up the kilns where calcination takes place. This makes cement production very detrimental to our climate. Even under optimum conditions, producing one ton of cement releases 1.4 tons of CO_2. Cement production currently accounts for 4 percent of worldwide anthropogenic CO_2 emissions.[18]

Figure 1.2 shows how industrial CO_2 emissions into the atmosphere have increased. The curve is dramatic. Just since World War II, industrial CO_2 emissions have increased fivefold, and the rate appears to be accelerating.

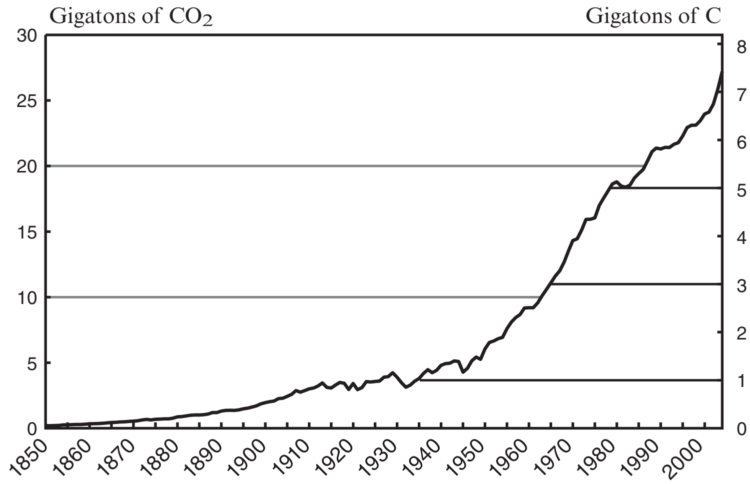

Figure 1.2
Annual global carbon emissions, with CO_2 emissions resulting from changes in land use, such as clear-cutting of forests, not considered. Source: *Climate Analysis Indicators Tool* (CAIT), Version 5.0, World Resources Institute, 2008, converted to gigatons of CO_2 (GtC).

The left-hand scale in figure 1.2 shows gigatons of carbon dioxide; the right-hand scale shows the gigatons of carbon contained in this CO_2. A gigaton is another name for a billion metric tons. In order to simplify comparisons with the carbon stocks still underground and with the carbon contents of fossil fuels, this book will normally base the weight specifications on the carbon content of CO_2. Because CO_2 contains two oxygen atoms attached to each carbon atom, and each oxygen atom is 1.33 times as heavy as a carbon atom, it is easy to establish a proportion between these two weights. You need only multiply the weight of the carbon contained in a specified amount of CO_2 by 3.66 in order to obtain the weight of that amount of CO_2. The chart shows that in 2005 the combustion of fossil fuels and the production of cement released 7.4 gigatons of carbon worldwide, equivalent to 27 gigatons of CO_2.[19]

The curve in figure 1.2 shows the yearly flow of carbon dioxide emissions. The area underneath the curve is the total stock of CO_2 emitted. For the greenhouse effect, what is important, of course, is not the stock emitted, let alone the annual flow of emissions, but the emitted stock that has not been absorbed by the oceans or by biomass. With forest clear-cutting included, humans have increased the stock of carbon in the atmosphere from about 600 to 800 gigatons of carbon since the Industrial Revolution, which corresponds to an increase in CO_2 density from 280 to 380 ppm.

Whether public policies can induce people to extract and release to the air less fossil carbon so as to slow down global warming, and if so how they can do so, is the main theme of this book, especially of chapters 4 and 5.

One more degree already

The big question is this: How is the anthropogenic increase in greenhouse-gas concentration affecting the temperature of our planet's surface? In view of the large temperature fluctuations between hot periods and ice ages that have always occurred, it is legitimate to ponder to what extent mankind has provoked the current climate change. Research has shown, for example, that in the second half of the fifteenth century a small ice age lowered temperatures in Europe by about 0.3°C (0.5°F). Three hundred years earlier, temperatures were 0.2°C (0.4°F) warmer than usual. About 18,000 years ago, when the last ice age came to an end, the world was 5.5°C (10°F) colder than it is now.[20]

A further difficulty in isolating the effect of human activity is that the temperature reacts very slowly to a change in heat radiation from the Earth. The new stable equilibrium resulting from the change in the greenhouse-gas concentration mentioned above will be reached very quickly from a geological point of view, but from our human perspective it appears to take much longer. It takes many decades until the warming process of air, rocks, and bodies of water has been completed. Whereas the temperature of the air in the layers in which airplanes fly (the troposphere) can change within a few days, in the stratosphere it can take much longer. Much slower still is the change in temperature at surface level, as the oceans, which react very sluggishly to climate change, exert a dominant influence there. Estimates say that the greenhouse gases already emitted since the pre-industrial period will raise the Earth's temperature by about 0.5°C (0.9°F) over today's average by the end of this century, even if the greenhouse-gas concentration were to remain stable from now on.[21]

However, despite this sluggishness, the Earth has already become noticeably warmer. This is evident from many indicators, among them

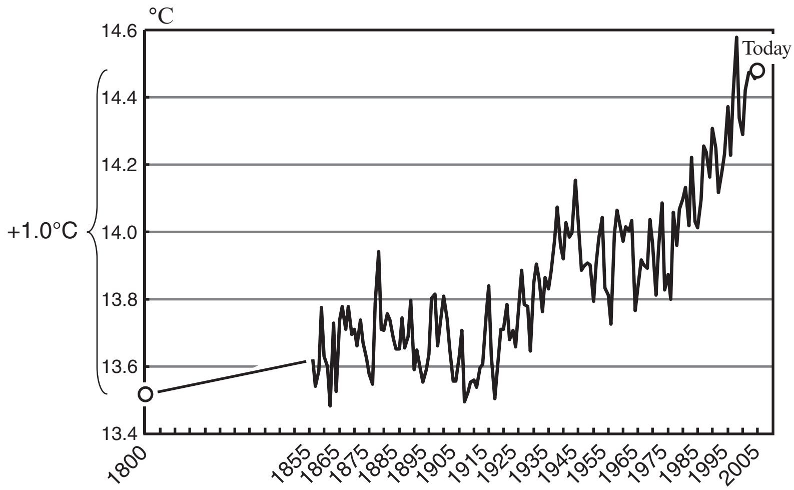

Figure 1.3
Global average temperatures measured by thermometers. Note: The global average temperature is calculated on the basis of measurements from 3,000 weather stations. The dot near the bottom of the left scale shows the pre-industrial temperature level in the year 1800, which according to Otto-Bliesner et al. amounted to 13.52°C (56.34°F). The most recent value for the current global average temperature, according to Jones et al., amounts to 14.48°C (58.06°F); this is depicted by the dot near the right-hand scale. Sources: P. D. Jones et al., "Global and hemispheric temperature anomalies—land and marine instrumental records," in *Trends: A Compendium of Data on Global Change*, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, 2006; B. L. Otto-Bliesner et al., "Last glacial maximum and holocene climate in CCSM3," *Journal of Climate* 19 (2006): 2526–2544.

direct temperature measurements made since the invention of the thermometer. Though there have been many fluctuations, the planet's average temperature seems to have already increased by about 0.7°C or 0.8°C since 1855, and has now reached 14.48°C (58.06°F).[22] Complex measurements using other indicators such as climate models and temperature anomalies even show an increase of nearly exactly 1°C (1.8°F) since the year 1800, when the average temperature was 13.52°C (56.24°F).[23] Figure 1.3 illustrates this.

The temperature curve in figure 1.3 should be interpreted with some caution. Measurement methods may have changed over time, and it isn't entirely clear whether the data have been properly adjusted for the effect of urbanization on the air surrounding measurement stations. At present, however, the curve depicted in the figure reflects the best available direct data on air temperatures.[24]

The temperature didn't increase equally everywhere; it rose more in inland areas than on those close to the coast, and more with increasing distance from the equator. In Germany, for example, a station in Potsdam shows an increase from 1890 to today from 8.3°C to 9.9°C (46.9 to 49.8°F), i.e., a 1.6°C rise, much higher than the global average.[25]

It is remarkable that the warmest ten years since the invention of the thermometer all occurred in the last eleven years (before this book first appeared in German). They were, in decreasing order of global average, the years 1998, 2005, 2003, 2002, 2004, 2006, 2007, 2001, 1997, and 1999.

Figure 1.3 shows that the temperature increase took place in two surges: one from 1900 to around 1945 and one since 1975. Over the period 1945–1975, practically no temperature increase was registered. This can probably be attributed to the high emissions of sulfur dioxide during the fast-paced economic development that took place after World War II. Sulfur dioxide is emitted when coal and oil are burned, and then is transformed into sulfate particles that block sunlight, leading to cooler temperatures on the Earth's surface. After measures to reduce air pollution and sulfur dioxide emissions were introduced globally, starting in the 1970s, this effect disappeared and the greenhouse effect took over again.[26] This interruption in global warming explains why the greenhouse effect only recently became of interest to both scientists and public opinion, and why it still was irrelevant during the oil crises of 1974 and 1982.

Whether there really is any anthropogenic global warming has been a subject of heated debate in recent years. Some skeptics, among them Scafetta and West,[27] argued that the increase in the temperature was due to a strong increase in the sun's radiation since about 1900. However, this argument was refuted by Benestad and Schmidt, who showed that only 8 percent of global warming in the twentieth century can be explained by that effect.[28] Lockwood and Fröhlich even showed that in the last quarter of the twentieth century, when the temperature was rising particularly rapidly (see figure 1.3), all changes in solar activity that in principle could have affected the temperature went in the "wrong" direction, slowing rather than accelerating global warming.[29]

Other skeptics claimed that the temperature measurement indicating global warming since the Industrial Revolution was flawed. Their criticism gave rise to the "hockey stick" controversy. A long-term data set provided by Mann, Bradley, and Hughes[30] had gained much popularity after being featured prominently in an IPCC report. The authors had reconstructed a temperature curve from proxy indicators, such as the widths of tree rings, the calcification rates of coral, and the composition of sediments, that showed that the temperature hadn't changed much during the last millennium except in the last 100 years. The curve representing the data looks like a hockey stick lying horizontally with its blade pointing up.

McIntyre and McKitrick[31] argued that the data set of Mann, Bradley, and Hughes was useless because the method for creating a temperature indicator from the proxy data was mistaken. They demonstrated that with the method that had been used to transform the proxy into temperatures even randomly chosen numbers would have produced a "hockey stick."[32]

The issue was discussed and re-investigated by a great many authors. Their findings are summarized in a report published by the National Research Council in 2006.[33] According to that report, nearly all other authors who delved into the issue found the global warming effect in proxy data, and the overwhelming majority confirmed the magnitude of the temperature rises of Mann et al. for the last 400 years, whereas there was more ambiguity for more remote periods of time. The data screened referred to, among other things, bore-hole temperatures, glacier lengths, tree rings, and various composite proxy indicators.

Meanwhile, the criticized authors invited others to join a bigger research program that would reconsider the issue. After correcting their previous mistakes, they presented a revised data set that resulted in essentially the same kind of "hockey stick" curve as before. This new data set was again criticized by McIntyre and McKitrick, and again the criticism was refuted by the original authors. There is an ongoing debate that, at this writing, has not yet come to a conclusion.[34]

Whatever its final outcome, this debate concerns only one of many data sets that have been collected and screened. The data sets leave little doubt about the global warming effect. One such data set is the direct measurement of temperature by thermometers, as in figure 1.3. The curve shown there isn't subject to the criticism of McIntyre and McKitrick, and doesn't contain proxy data.

The past 800,000 years

Truly fascinating data were obtained from ice-core drilling done in Antarctica by an international team of researchers working under the auspices of the European Union's Project EPICA. The researchers managed to bore into the Dome C ice mountain to a depth of 3,270 meters (10,726 feet), reaching 800,000 years into the past and thus amply surpassing the previous record of 650,000 years.[35] They obtained data on the CO_2 concentration in the atmosphere and on air temperatures.

The CO_2-concentration data came from air bubbles trapped in the Antarctic ice, which consisted of compressed snow that had accumulated without ever melting.

How the temperature data were obtained is less straightforward. After all, ice is equally cold everywhere. But temperature data can be reconstructed by means of the isotope method, an ingenious method that has fundamental significance in climate research. Water consists of hydrogen and oxygen atoms, which aren't homogeneous; they can vary according to the number of neutrons contained in their nuclei. A variation resulting from different numbers of neutrons in the nucleus is called an *isotope*. Water containing oxygen 16 and water containing oxygen 18 evaporate at different speeds. Oxygen 16 makes for lighter water, oxygen 18 for heavier water. Because lighter water evaporates faster than heavier water, the ratios of the two isotopes in Antarctic ice cores provide precise indications of the temperatures that prevailed in previous periods. These ratios reveal the temperature of seawater that subsequently evaporated, was transported by the wind over Antarctica, precipitated there as snow, and eventually became compressed into Antarctic ice. The great advantage of the isotope method is that it can be carried out using the same ice cores used to determine the CO_2 content of the air bubbles trapped in them. This makes it possible to derive data on CO_2 content and temperature from the same sample. (See figure 1.4.)

At present, the Earth's average temperature on the surface is 14.5°C (58°F), as mentioned above. This is the highest average temperature not only in the past few years but in the past 100,000 years. It was last higher during the Eemian Interglacial, a warm period that began 128,000 years ago and lasted 11,000 years. That was the warmest period in the last 800,000 years, during which humankind evolved from *Homo erectus* to *Homo sapiens*. During the Eemian Interglacial, the Earth's average surface temperature exceeded the average of the past 800,000 years, which was about 11°C, by 4°C—that is, it reached about 15°C (59°F). With our 14.5°C, we are close to this. Obviously we are living through one of the warmest periods in human history.

Figure 1.4 shows a temperature curve covering the last 800,000 years. The time axis requires a bit of mental adjustment, as each space between

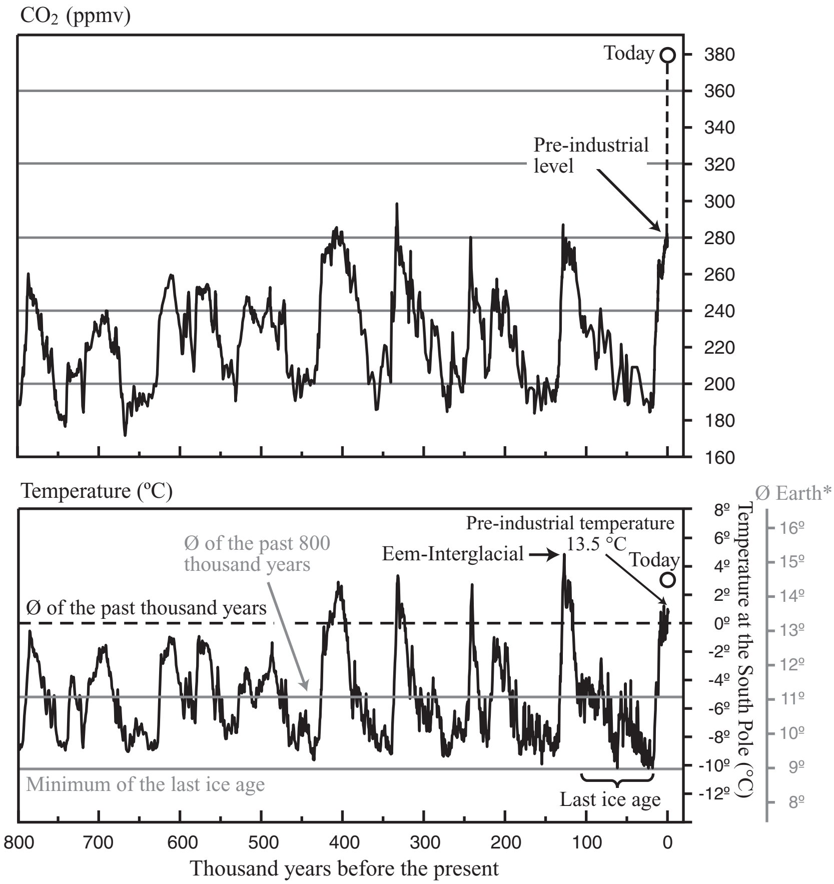

Figure 1.4

Ice-core drillings. The temperature scale on the right side of the upper panel shows the deviation of Antarctic temperature from its average of the past 1,000 years; that on the right side of the lower panel shows the corresponding average temperature. This scale was based on other data that were adjusted according to the following information: (1) The last value in the temperature curve shows the Antarctic temperature in the year 1912. This temperature lies exactly 0.88°C above the average of the past 1,000 years. (2) The lowest Antarctic temperature during the last ice age (about 18,000 years ago) was 10.2ºC (1.56°F) below the mean of the last 1,000 years. (3) In 1912, the average temperature was 13.6ºC (56.5°F), 0.1ºC above the "pre-industrial" temperature in the year 1800; see figure 1.3. (4) According to Otto-Bliesner et al., the average temperature during the coldest period of the last ice age was 8.99ºC (48,18°F). Sources: D. Lüthi et al., "High-resolution carbon dioxide concentration record 650,000–800,000 years before present," *Nature* 453 (2008): 379–382; J. Jouzel et al., "Orbital and millennial Antarctic climate variability over the last 800,000 years," *Science* 317 (2007): 793–796; B. L. Otto-Bliesner et al., "Last glacial maximum and Holocene climate in CCSM3," *Journal of Climate* 19 (2006); 2526–2544; own calculations.

bars represents 50,000 years. The numbers are counted backward from the present. The "current" average CO_2 level, spanning the last 500 years, is shown on the right side of the CO_2 curve. It amounts to 280 ppm, which, as was mentioned above, corresponds to its pre-industrial value.

Figure 1.4 has two temperature scales, both on the right side. One shows deviations in Antarctic temperature from the average of the past 1,000 years; the other translates these temperatures into a global average temperature. The zero value on the left-hand scale corresponds to a 13.3°C (55.9°F) global average on the right-hand scale. According to figure 1.3, this average was slightly lower than the one prevailing during pre-industrial times, i.e., 13.5°C (56.3°F). The right-hand temperature scale is somewhat more stretched than the left-hand one, because the average temperature over most parts of the planet doesn't show such strong swings as the temperature in Antarctica.

The last ice age can be clearly made out in the period from 115,000 to 10,000 years ago; it reached its coldest period 18,000 years ago, with an average of just 9°C (48°F). The Eemian Interglacial also can be seen clearly. It occurred around 125,000 years ago, with an average temperature of 15.3°C (59.5°F).

It is striking how much the Earth's temperature has fluctuated. The fluctuations can be attributed to disturbances that affect the amounts of energy received and radiated. One of the disturbances is the regular displacement of the Earth's axis. Like a top, the Earth wobbles as it rotates more slowly. The Earth's axis wobbles at a rate of about one spin every 26,000 years. This wobbling leads to a change in the amount of radiation received by the planet's darker and lighter areas, changing the amount of heat they absorb. Meteorite impacts and volcanic eruptions can also influence our climate: the dust they release into the atmosphere reduces the amount of sunlight reaching the surface, while the carbon dioxide they also release works in the other direction, increasing the greenhouse effect. In addition, solar radiation has itself experienced large variations over time, as shown by the sunspot phenomenon. All these factors have combined to create the fluctuations in our climate depicted in figure 1.4.

Today's values, those measured directly from the atmosphere, are also shown in figure 1.4. They amount to 380 ppm of carbon dioxide and an average global temperature of 14.5°C (58.1°F). These values, when set against the Earth's geological ages, illustrate the uniqueness of our current situation. There was never, over the 800,000 years shown, as much carbon dioxide in the atmosphere as there is now,[36] and the temperature now also hovers in the upper ranges, exceeded only occasionally during the interglacial warm periods.

Correlation and causality: A solvable puzzle

It is striking how closely correlated the CO_2 curve and the temperature curve are. On the face of it, one could take this correlation as proof of the greenhouse effect. It looks as if the changes in the atmosphere's CO_2 content have influenced the temperature. Closer examination, however, shows that this can't be correct, as most of the temperature extremes occurred a bit earlier than the corresponding peaks in CO_2 content. The data show that the Earth's temperature changes occurred, on average, about 800 years before the changes in the atmosphere's CO_2 content. This eliminates the possibility that the greenhouse effect was the major force behind the correlation observed.

The real reasons for the correlation are found in the fizzing effect, in the permafrost effect, and in biological processes. These effects were mentioned previously in relation to the self-energizing processes of the greenhouse effect. When external influences that increase incoming solar radiation lead to an increase in Earth temperatures, the oceans' capability for storing CO_2 decreases, their waves instead transferring this gas into the atmosphere. The permafrost areas, in turn, begin to thaw and release CO_2 through the decay of organic matter, either directly or through the production of methane, which quickly decays through oxidation into CO_2. With higher temperatures, the carbon stored in biomass will also be reduced, as deserts will expand. The opposite occurs when temperatures decrease. In that case, the oceans will again absorb more CO_2 and, up to a certain point, more plants will grow, their photosynthesis capturing CO_2 from the atmosphere and storing it as biomass. All these effects explain why temperature oscillations bring about a corresponding fluctuation in the atmosphere's CO_2 concentration.

Some skeptics have used these findings to cast doubt on the assertions about the effects of greenhouse gases on our climate. It is claimed that climate researchers have manifestly misinterpreted the correlation observed by attributing temperature fluctuations to the variations in the atmosphere's CO_2 content. Thus, skeptics say, the entire climate discussion that has caused such an uproar around the world is based on a fallacy, and we should therefore desist from introducing measures to reduce industrial CO_2 emissions.

These arguments are hollow. No serious climate researcher has ever asserted that the correlation between CO_2 content in the atmosphere and temperature was due to temperature-independent disturbances in CO_2 content in the atmosphere. In fact, climate researchers have arrived at their conclusions essentially through theoretical models and refined statistical methods that stand above the allegation that they are based on a mere interpretation of the correlation observed.

As was explained above, the central element in the theoretical explanation is the absorption of infrared back-radiation by the greenhouse gases. This absorption is a physical effect firmly established in theory and confirmed by many experiments. Direct proof of this absorption has been provided in recent years by spectral measurements from satellites. Since the satellites are outside the atmosphere, they make it possible to measure the back-radiation behind the "atmospheric filter." The measurements show that the spectral frequencies CO_2 is known to absorb from theoretical considerations and experiments are indeed being absorbed, thus warming the atmosphere.[37]

A particularly interesting result was published in 2001 by Harries, Brindley, Sagoo, and Bantges,[38] who compared spectral measurements made in 1970 by a NASA satellite against spectral measurements made in 1997 by a Japanese satellite. After showing that the two data sets were comparable, Harries et al. found that the relevant infrared back radiation filtered out by the greenhouse gases had been substantially reduced over the measurement period. Thus, the temperature increase over this period can indeed be largely attributed to the greenhouse effect.

It is true that the correlations shown in figure 1.4 are due predominantly to the permafrost and fizzing effects rather than to the greenhouse effect. But the reason is simply that variations in solar radiation are bigger and more frequent than exogenous variations in greenhouse-gas concentration in the atmosphere, for which, except for the human influence, little other than volcanic eruptions would come into consideration. The predominance therefore doesn't imply that there is no greenhouse effect. Usually a car comes to rest because the driver has stepped on the brake pedal. More seldom, one comes to rest because it has run into an obstacle. The fact that the former cause empirically occurs more often than the latter doesn't mean that the latter cause is irrelevant and not worth trying to avoid.[39]

The changes in CO_2 content in the atmosphere caused by temperature variations have not caused the climate fluctuations over geological periods, but they have amplified them. The fact that these fluctuations have attained the magnitudes depicted in figure 1.4 is also due to an accelerator or feedback effect stemming from the greenhouse gases that the rising temperatures caused the ocean water to expel.[40] Even though exogenous variations in CO_2 were rare before industrial times, CO_2 has always played an important part in making the temperature variations as large as they were. When the oceans were being warmed by increased radiation from the sun and were releasing more CO_2 , the additional CO_2 then warmed the planet even more. This is reason enough to be afraid of the exogenous variations brought about by industrialization.

Unfortunately, as was mentioned above, we are currently living through a warm period. If we were in the midst of an ice age, the additional global warming resulting from industrial greenhouse gases would be quite welcome. It would counteract the geological cycle and exert a stabilizing effect. The reality is, however, exactly the opposite. During pre-industrial times the global temperature was already above its long-term average. Now man-made effects are exacerbating the increase, bringing it to levels resembling the peaks of the past million years.

We are burning carbon stocks that were essentially formed during the Carboniferous period, from 280 million to 340 million years ago, from vast forests. The burial of large forest areas as a result of tectonic movements led to the formation of bogs in which new plants grew, died, and gradually sank ever deeper. The resulting coal, oil, and natural gas were removed from the biological cycle until man began pumping them back into that cycle once again.

The stocks of fossil fuels played no part in the fluctuations of CO_2 content in the atmosphere shown in figure 1.4. They lay so deep that no oxygen could reach them; thus, they were not able to burn or otherwise oxidize and thus release carbon dioxide. These fluctuations were essentially results of the displacement of a given amount of carbon between the oceans, biomass, and the atmosphere brought about by the fizzing water effect and by biological processes. Only volcanic eruptions on the planet's surface increased the amount of carbon in circulation, but that effect was relatively marginal. Volcanic emissions account for only one-tenth of a gigaton of carbon per year, equivalent to only 1.25 percent of the yearly anthropogenic emissions.[41]

The climate-change problem arises from the fact that mankind has increased the amount of carbon cycling through the atmosphere, the oceans, and biomass by adding fossil carbon that formed during the Carboniferous and had lain undisturbed, not taking part in nature's carbon cycle, for millions of years. Over the next 500 years—a vanishingly short portion of the time span represented in figure 1.4—we will tap, and perhaps exhaust, a reservoir that took about 120,000 times as long to form. This will lead to a break in the trend of the temperature curve and will cause a lasting increase in the average measured over ice ages and interglacial periods, regardless of variations caused by disturbances in solar radiation that bring about fluctuations between warm and cold periods. Of course it is possible that, as was the case during the Carboniferous, tectonic changes in the Earth's crust will again remove carbon permanently from the carbon cycle. That, however, should not be expected in, say, the next 800,000 years. Humans will have disappeared from this planet before the new carbon is removed from the cycle and again stored in the crust.

On to the North Pole

The first consequences of global warming are visible in many places. Photographs taken during the first half of the twentieth century show clearly that the glaciers in the Alps are retreating. The area of the Watzmann glacier, for instance, shrank by 64 percent from 1897 to 2006, that of the Northern Schneeferner glacier by 70 percent from 1892 to 2006, and that of the Southern Schneeferner glacier by 90 percent from 1892 to 1999.[42] The Arctic is another case in point. In the years 1996–2006, the area of the ice sheet over the North Pole shrank by 1.5 million square kilometers (580,000 square miles), 23 percent of its total area. The shrinkage was so extreme that during the summer of 2007 the Northwest Passage between Alaska and Labrador was ice-free for the first time, prompting Russia to quickly proclaim its sovereignty over the Arctic.

Our planet warms more rapidly over the North Pole than over the South Pole because it has more land surface and less ocean in its northern portion, even though the South Pole lies over a continent and the North Pole over an ocean. The South Pole has been so cold, and will remain so cold for the foreseeable future, that its ice can't be expected to melt during this century.[43]

So far, because only the North Pole's ice is melting, the sea has risen very little from its level during the pre-industrial period. Ice that melts in the ocean can't raise the water level. If an iceberg melts, the melted water exactly fills the space below the surface that the iceberg displaced before. One cause of the rise in sea level is the melting of glaciers in the Northern Hemisphere. The most significant contributor in this regard would be Greenland's ice cap. Greenland was settled during a warmer period, around the year 1,000, by a Viking known as Eric the Red, but then it turned too cold for further settlement. Today, once again, it is literally flourishing. Even orchids are blooming there now. The forecasts are that an increase of the global average temperature of about 2 to 3 Celsius degrees relative to pre-industrial times will cause the Greenland ice cap to begin to shrink.[44] If all ice disappeared there (something that would take hundreds of years), the sea level would rise by about 6 meters. Another cause of sea-level rise is that water expands as it gets warmer. The two effects combined have caused only a 20-centimeter rise in sea levels until now,[45] but more is to come.

How warm will it get?

How much will the temperature on the surface of our planet rise, and what consequences will that have for life?

We should not expect the worst. Life on our planet will not be wiped out by the greenhouse effect. The relevant models can allay our fears. Earth's physical properties make a runaway process like that on Venus impossible. Such a runaway process would be imaginable if the human-caused increase in the atmosphere's carbon dioxide content were to escalate to a self-energizing reaction that would lead to ever more heat, ever more water vapor, and a release of the carbon dioxide contained in the oceans until the planet literally began to boil.[46] One reason that can't happen is that Earth receives only half as much solar radiation as Venus.

Nevertheless, tipping events could lead to an acceleration of global warming even if the temperature initially rises only a little.[47] If the Greenland ice sheet and the ice on Antarctica no longer cover dark-hued land, more sunlight will be absorbed, and warming will accelerate. A similar effect is operating in the Arctic. Though the melting of the Arctic ice itself doesn't raise the sea level, open-sea water absorbs more solar radiation, which accelerates global warming. Moreover, an increase in temperatures can destroy the complex equilibrium of tree physiology, fire, and rainfall in the boreal forests (coniferous forests in the Russian taiga and northern Canada), in the Amazon rainforest, or in the West African monsoon regions, killing the trees and setting free the carbon that had been captured in them. Melting of permafrost regions results in the release of huge amounts of methane and CO_2, which further accelerates global warming.

What *could* happen is bad enough, as was pointed out by a commission appointed by the British Government and led by Nicholas Stern, a former chief economist at the World Bank.[48] The Stern Commission's report, published in 2007, received widespread attention and has provided a strong impetus to public debate of global warming in recent years.

The Stern Commission examined alternative scenarios for the further evolution of the global climate. In the most likely alternative in their calculations—the business-as-usual (BAU) case—the commission concluded that the carbon dioxide concentration in the atmosphere will have risen from 280 ppm around the year 1800 through today's 380 ppm to 560 ppm by 2050. In the worst-case scenario, this concentration could come to pass as early as around the year 2035.[49]

The rise in temperature associated with this increase in carbon dioxide amounts to 3°C (5.4°F) over the pre-industrial average, i.e., 2°C over today's level. This would be enough to make Greenland's ice cap begin to melt. The temperature on the surface would rise from its pre-industrial average of 13.5°C (56.3°F; in 1800), through today's average of 14.5°C (58.1°F), to 16.5°C (61.7°F). This would be a substantial acceleration of the pace prevailing in the past 150 years. As a comparison with figure 1.4 shows, it would become the highest temperature in 800,000 years. The 15.3°C (59.5°F) record of the past 800,000 years may be broken as early as 2030.

If humanity does nothing, the atmospheric CO_2 content will continue rising unabated. How far it will go is debatable, as no one can predict with certainty how rapidly the world's economy will grow and how the owners of fossil-fuel resources will react to the various incentives they face. Even the best economist with the most sophisticated models can only calculate scenarios on the basis of a set of assumptions that themselves are not predictions but merely plausibility considerations. The Stern Commission investigated a range of very different trend extrapolations published in the literature, in particular those of the IPCC. In what they considered the most plausible scenario for the business-as-usual case, the CO_2 concentration would rise to 900 ppm by 2100, which equates to a temperature of 18.6°C (65.5°F), 5.1°C (9.2°F) above the pre-industrial level.[50]

The Stern Commission's business-as-usual scenario corresponds roughly to the A1FI scenario of the 2001 IPCC Report. According to the latter, the world's population would increase from 6.5 billion to only 7.1 billion by 2100, but global GDP would soar from 48.5 trillion US dollars to about $525 trillion at today's prices. Yearly global carbon dioxide emissions would increase fourfold from their 1990 levels to 30.3 gigatons of carbon.[51] The A1FI scenario is one of a whole family of scenarios investigated by the IPCC. All of them assume that globalization progresses rapidly, leading to fast economic growth and a rapid regional convergence of living conditions. According to the A1FI scenario, the world's population will reach its maximum around the middle of the century, and the developing countries will progress so quickly that their per-capita income will reach two-thirds of that of developed countries. It also assumes that energy will continue to be obtained from the intensive burning of fossil fuels.

A2, an alternative scenario, assumes that the world's regions will not converge so quickly. Developing countries' per-capita income will not rise above one-fourth of that of developed countries until 2100, because those countries will fail to get their population growth under control. The world's population will thus increase to 15 billion by 2100, with GDP rising to only $250 trillion at today's prices. Figure 1.5 illustrates these two projections.

It is to be hoped that neither scenario will prove true, and that humanity will manage to curb CO_2 emissions in time. These scenarios, however, are realistic trend extrapolations of the case where we do nothing and continue business as usual. They aren't even the most pessimistic scenarios. Because we can forecast self-energizing effects in climate only up to a point, things could be significantly worse. The range of dispersion in figure 1.5 shows how far deviations in either direction could go. The most optimistic scenarios project a 3°C (5.4°F) increase in global average temperature over pre-industrial levels; the most pessimistic ones project 6°C (10.8°F).

Lately, reports suggesting that the more pessimistic scenarios are becoming more likely seem to be proliferating. In November 2008, the head of the International Energy Agency (IEA), a research outfit supported by the Organisation for Economic Cooperation and Development,

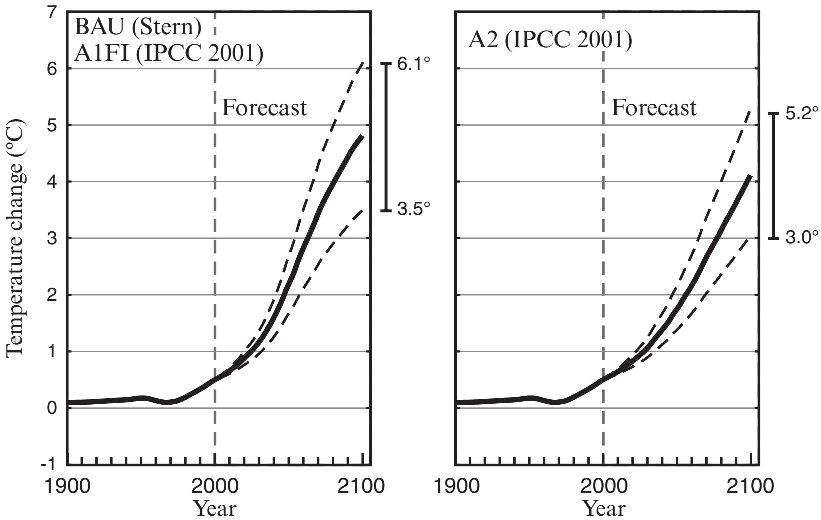

Figure 1.5
Temperature increase forecasts in the absence of a climate policy. The A1F1 scenario of the IPCC TAR Report 2001 corresponds roughly to the Stern Commission's business-as-usual scenario. Dashed lines depict how the projections vary according to changes in assumptions. Sources: J. T. Houghton, Y. Ding, D. J. Griggs, M. Noguer, P. J. van der Linden, X. Dai, K. Maskell, and C. A. Johnson, *Climate Change 2001: The Scientific Basis*. (Cambridge University Press, 2001), p. 554; calculations by H.-W. Sinn.

located in Paris, and employing 190, claimed that the Earth would warm by 6°C by the year 2100 over the pre-industrial average (i.e., 5°C over today's average) if we were to fail to adopt radical measures forthwith.[52] This assertion fits with the Stern Commission's BAU scenario and with the IPCC's A1FI scenario. Nicholas Stern himself has, in the meantime, made even more alarming statements. He calls for carbon dioxide emissions to be halved by 2050 relative to the 1990 levels.[53]

Those who think a 5–6°C temperature increase is not much should bear in mind that this is the amount by which the average temperature has risen on our planet since the peak of the last ice age, 18,000 years ago. What took 18,000 years would now come to pass in only 100.

On top of that, the rise in temperature would not be spread equally across the Earth. The oceans would become 4°C (7.2°F) warmer, Western Europe 6°C (10.8°F) warmer, and northern Finland and Siberia no less than 8°C (14.4°F) warmer. The average temperature would reach 19–20°C (66–68°F), thus exceeding by 4–5°C the maximum attained in the past 800,000 years. That would change how humans live and how they interact. With such temperatures, humanity would enter, in the words of the Stern Commission, "unknown territory."

What is so bad about it?

Not everyone shares these concerns. What would be so bad about the Earth's becoming a bit warmer? What is the big deal about a couple more degrees by 2035 and four or five more by 2100? Isn't it too cold in most of the Northern Hemisphere anyway? Those who find it a bit chilly sitting on their terrace on a summer evening would not mind a couple of degrees more. And, after all, do we not vacation in the sunnier, warmer spots? In the tropics, the air is about 17°C (31°F) warmer than in northern Europe, and even in northern Italy it is 5.5°C (10°F) warmer than in, say, Germany.[54] If the Italian weather were to be transferred to Germany, Germans would be able to save transportation costs on their summer jaunts. It can't be all that bad.

And then, think of Siberia. The largest contiguous land mass stretches from Norway to northern China, but a significant portion of it is too cold for agriculture. The permafrost regions of the former Soviet Union cover an area of 11 million square kilometers, one-tenth more than the land area of the United States. Wouldn't it be a good thing if those places could be a bit warmer, allowing more people to live there? Furthermore, if Russia's Arctic Sea were open to shipping thanks to the polar ice retreating, a brisk sea trade could develop, linking newly flourishing coastal towns with each other. True, Sicily might wither away, but how big is Sicily in comparison with Siberia?

Such views, however, betray superficial knowledge. Technical literature has substantiated the following effects:

- Savannahs and deserts would expand. The subtropical regions, home to many people today, would be assailed by droughts. Droughts affect the entire Mediterranean region even now, but they would extend to Western Africa, Mexico, California, and Australia and make life difficult there.[55] Heat waves like the one in 2003 that caused the death of 35,000 people, 15,000 of them in Paris,[56] would become more common, as would brush and forest fires, which even today regularly sweep through southern Europe, California, and Australia.

- Sea-level rise would continue, exacerbated by the melting of continental ice masses (particularly the Greenland icecap) and by the expansion of sea water caused by higher temperatures.[57] Estimates point to a rise of 1 meter (3.28 feet) from pre-industrial levels by the end of this century. That would cause problems not only in Bangladesh but also in many other coastal areas. The Netherlands would be the most affected country in Europe.[58] The Dutch would surely have no problem raising their dikes another meter, but how they would dump the flow of the Rhine into the North Sea is a matter of heated debate even now.
- Because higher average temperatures mean higher temperature differences between regions, between land and sea, and between air layers, air movements would become much stronger. Hurricanes and typhoons would increase in number and in force.[59] The southern United States and Japan and other Asian island states would be particularly affected.[60]
- The shifting of the habitable regions would lead to migrations akin to those that occurred during the ice ages and the interglacial periods.[61] Large migration flows from south to north could be expected in the Northern Hemisphere. This would not happen without armed hostilities, ethnic conflicts, civil wars, and great social penury. The world would have to find a new settlement structure.[62] This is certainly the greatest potential peril presented by the greenhouse effect.
- Changes in weather patterns associated with climate change probably would affect human health, in particular owing to changes in the distribution of infectious disease vectors and increased risk of respiratory and skin diseases.[63]

There is also the fear that the Gulf Stream might stop flowing if more fresh water were to reach the oceans. That would have dramatic consequences for Western Europe, which, contrary to the general trend, would develop into a cold zone. Europe north of the Alps would be barely inhabitable, with climatic conditions similar to those prevailing in northern Canada. This concern is, however, not shared by most of the literature. At most, a weakening of the Gulf Stream is expected, which would not necessarily be bad for Western Europe because it might counteract the global warming. According to a new study by the Leibniz Institute of Marine Sciences (also known as IFM-Geomar), no weakening of the Gulf Stream has yet been detected. Even if the Gulf Stream were to cease to flow altogether, the warming trend in Europe would merely grow somewhat weaker.[64]

And, as was mentioned above, we need not fear that the South Pole will become so warm in the next 100 years or so that the ice there will begin to melt. But if temperatures were to continue to increase far beyond that, so that one day even the Antarctic ice would melt away, sea levels could rise by 61 meters, if only after hundreds of years.[65] In that case, the Netherlands would lie nearly completely under water, and Düsseldorf, Hannover, and Berlin would become seaports. Hardly anyone dares to deal with such projections.

The Stern Commission tried to calculate the consequences of global warming in monetary terms. For the BAU scenario, according to which temperature rises to about 4.5°C above the present level (5.5°C above pre-industrial level), they estimate an annualized damage of between 5 percent and 10 percent of annualized world consumption, "now and forever."[66]

Measures to avoid and mitigate this temperature increase by reducing CO_2 emissions are also expensive, but they would still be cheaper for humanity, according to the Stern Commission. The Review estimates annualized mitigation costs of around 1 percent of annualized world consumption if the temperature increase is limited to 2°C above today's level or, equivalently, CO_2 concentration of 550 ppm.[67] Relative to the BAU scenario, mitigation of this extent would reduce the damage by between 2.8 percent and 5.6 percent of consumption (2.5/4.5 of the above-mentioned annualized damage figures for a 4.5°C increase). Thus, the annualized net gain from a mitigation strategy aimed at limiting the temperature increase to 2°C above today's level would be between 1.8 percent and 4.6 percent of annualized consumption. Even though the numerical calculations behind such numbers rest on many assumptions and are therefore not free from arbitrariness, they do provide a learned argument for why, from an economic point of view, there is a case for acting now to slow climate change. An arguably stronger qualitative case leading to the same conclusion will be presented in chapter 4.