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The Earth's Climate and Ongoing Global Change

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1.1 Introduction

The aim of this chapter is to provide a solid, objective, and quantitative review of the key aspects of climate change. Before beginning this analysis, it is worth noting that the fact that Planet Earth has a greenhouse effect is not, in and of itself, negative. Indeed, this effect has directly facilitated the evolution of complex forms of life – the Earth's temperature would be about 30°C colder were it not for the atmospheric greenhouse effect.

The problem of climate change that we are experiencing now is caused by the amplification of the greenhouse effect due to emissions from human activities. As greenhouse gases have been accumulating in the atmosphere since pre-industrial times, and more rapidly after World War II, the Earth has been experiencing global warming on a very fast timescale, which has caused profound environmental changes across tens of years instead of tens of thousands of years as occurred in the distant past.

After this short introduction, in the first section we will analyse observed trends in greenhouse gases, before in Section 1.2 discussing observed climate change and its impacts. In Section 1.3, we will review the total and per-capita greenhouse gas emissions of principal emitters (that is, major countries or groups of countries such as Europe). In Section 1.4, we will look at the quasi-linear link between the greenhouse gases accumulated in the atmosphere and global warming, and investigate the emission limits required if we are to contain global average warming below 1.5°C or 2.0°C. Finally, we will summarize and link all these topics, and discuss the level of global average warming that we could face in 2050 under four possible emission scenarios – one with a continuous future increase of greenhouse gas emissions of 1% per year, and three with a continuous future decrease of greenhouse gas emissions by 1%, 3%, or 5%, respectively. We will also point out that if we want to reach net zero emissions by 2050, we actually need to be even more drastic in our reductions, and aim for an average 8% annual decrease.

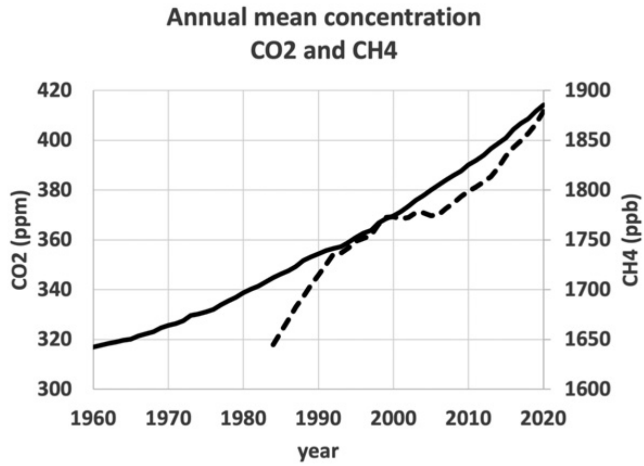

Figure 1.1 Annual mean concentration of carbon dioxide (CO_2, solid line; in parts per million, ppm) and of methane (CH_4, dashed line; in parts per billion, ppb), measured at the Mauna Loa Observatory. *Source*: Carbon dioxide data provided by Dr Pieter Tans, NOAA Global Monitoring Laboratory, Boulder, USA (gml.noaa.gov/ccgg/trends/) and Dr Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu/). Methane data provided by Ed Dlugokencky, NOAA Global Monitoring Laboratory, Boulder, USA (gml.noaa.gov/ccgg/trends_ch4).

1.2 Growing Concentrations of Carbon Dioxide and Methane

The concentration of greenhouse gases has been increasing since the start of the industrial revolution. Figure 1.1 shows the annual mean concentrations of atmospheric carbon dioxide (CO_2) and methane (CH_4) since 1960.[1]

In 2015, the concentration of carbon dioxide passed the 400 parts per million (ppm) mark, a value that the Earth last saw about two and a half million years ago.[2] Note also that the increase follows an exponential curve, and that the annual percentage increase has been continuously growing. For example, while in the 1960s and 1970s the annual percentage increase was between 0.2% and 0.4%, in the last two decades it has been above 0.5% (Figure 1.2). Further consider that the last two decades have seen a positive trend, with the growth rate increasing by about 0.01 every year, from about 0.47% in 2000 to about 0.65% in 2020.

Methane concentrations have also been increasing from about 1,645 ppb in 1985 (figures from before 1985 are not available) to 1,879 ppb in 2020 (Figure 1.1). Figure 1.2 shows that the annual growth rate had been decreasing between 1985 and 2000, but since then values

[1] Data collected at the Mauna Loa Observatory (Hawaii) of the United States National Oceanic and Atmospheric Administration (NOAA).

[2] See, for example, J. M. Wallace and P. V. Hobbs, *Atmospheric Science: An Introductory Survey*, 2nd ed. (Academic Press, 2006), p. 484; D. L. Hartmann, *Global Physical Climatology*, 2nd ed. (Elsevier, 2015), p. 470; Summary for Policymakers, in V. Masson-Delmotte et al. (eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC, 2021).

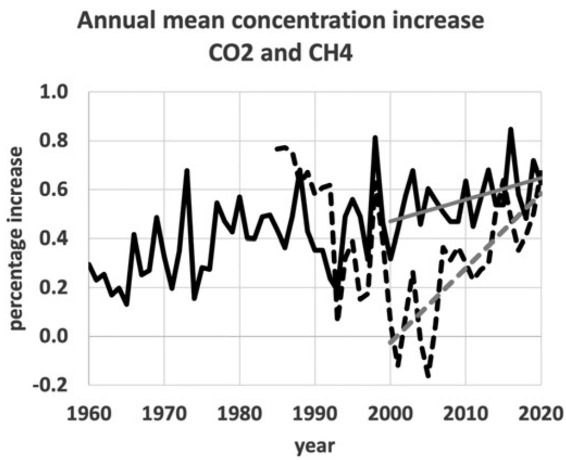

Figure 1.2 Annual percentage increase in the concentration of carbon dioxide (CO_2, solid line) and of methane (CH_4, dashed line), computed from the Mauna Loa Observatory data shown in Figure 1.1. The two lines show the best linear-fit straight lines that fit the data between 2000 and 2020. *Source*: Data provided by NOAA Global Monitoring Laboratory, Boulder, USA (https://gml.noaa.gov).

have been growing at a very rapid rate. The last two decades have seen a clear trend, with the growth rate increasing by about 0.03% every year, from about 0% in 2000 to 0.60% in 2020. This increase could be linked to the fact that, beginning in 2000, many countries began switching to methane as a means of electricity production. This increase can also be attributed to the melting of the permafrost – a layer of subsurface soil that is typically frozen year-round, especially near the poles – which has released yet more stored methane into the atmosphere.[3]

1.3 Observed Global Warming

As the concentration of greenhouse gases has steadily increased, the atmosphere has been absorbing more long-wave radiation emitted by the Earth, with the result that its lower layers have been warming, causing more long-wave radiation to be redirected back towards the Earth's surface, warming it as well.

Figure 1.3 shows the anomaly of the global annual mean temperature with respect to the pre-industrial value (that is, for each year, the figure shows the difference between the global annual mean temperature of that year and the global annual mean temperature in the period 1850–1900). The solid line shows the annual values, and the linear-fitted straight line with a slope of ~0.02°C/year (degree centigrade per year) shows the long-term warming trend. Note that superimposed upon this linear warming trend of ~0.2°C per decade are natural oscillations of about 0.1–0.2°C. These natural oscillations are due to natural changes in the

[3] M. R. Turetsky, B. W. Abbott, M. C. Jones, et al., Permafrost collapse is accelerating carbon release. *Nature* 2019, 569: 32–24.

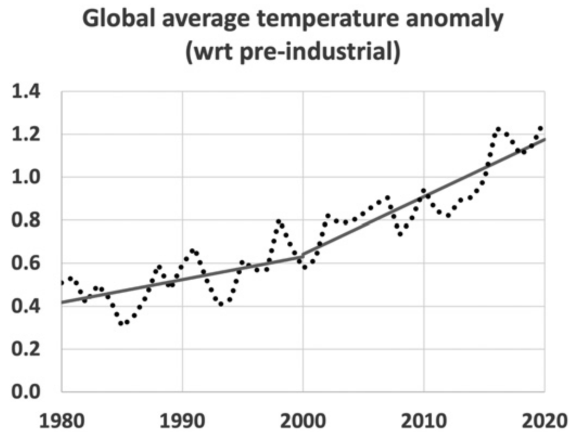

Figure 1.3 Land-surface global warming with respect to the pre-industrial level between 1980 and 2020. The dotted line shows the annual average anomalies of the land two-metre temperature, where the anomaly has been computed with respect to the pre-industrial level. The two straight lines show the best linear fit lines between 1980–2000 and 2000–2020. *Source*: Generated using Copernicus Climate Change Service information (2022) available at https://climate.copernicus.eu.

Earth's ocean, and atmospheric conditions linked, for example, to the occurrence of large-scale episodes in the tropical Pacific that are associated with warmer (during El Niño events) or colder (during La Niña events) ocean temperatures. Exceptionally large volcanic eruptions have also resulted in temperature variations in the following 1–3 years.

This figure has been created using a very recent data set produced by the EU Copernicus Service, the ERA-5 reanalysis, constructed by assimilating all available observations of the Earth system with the European Centre for Medium-Range Weather Forecasts' (ECMWF) state-of-the-art model.[4] It covers the satellite era, that is, the period from 1980 onwards during which satellite data have allowed a more accurate monitoring of the Earth. Because ERA-5 spans an era during which the number and quality of observations have not varied in such a way as to affect estimates of Earth's climate, and as it processes all available observations using a state-of-the-art Earth-system model, it provides a very valuable and high-quality estimate of how the Earth's climate has been evolving in this period.

Figure 1.3 shows that in 2020 the global average temperature was about 1.2°C warmer than the pre-industrial level, up from about 0.5°C in 1980, and that the six years from 2015 to 2020 were the six warmest years since 1980. Figure 1.3 also shows that the warming trend of the last two decades, 2000–2020, has been higher than that between 1980 and2000, increasing from 0.01°C per year (that is, 0.1°C every 10 years), to 0.026°C per year (0.26°C every 10 years). Table 1.1 reports the trends computed for the two periods, 1980–2000 and 2000–2020, expressed in terms of variations over 10 years, for several key climate surface variables.

[4] H. Hersbach, B. Bell, P. Berrisford, et al., The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society* 2020, 146(730): 1999–2049.

Table 1.1 *Linear trends over 10 years, computed over two periods – 1980–2000 and 2000–2020 – for a few key surface climate variables: global annual average two-metre temperature (2mT; second row), global annual average sea-surface temperature (SST; third row), Arctic minimum sea-level extension (fourth row), and global average sea-level rise (fifth row). Trends have been computed using data from Copernicus for SST and 2mT, and from* Our World in Data *(Arctic extension and sea-level)*

Variable	Linear trend over 10 years	
	1980−2000	2000−2020
Global annual average two-metre temperature	0.10°C	0.26°C
Global average sea-surface temperature	0.14°C	0.18°C
Arctic annual minimum sea-ice extension	−6.21%	−13.1%
Global average sea-level rise	1.76 cm	3.6 cm

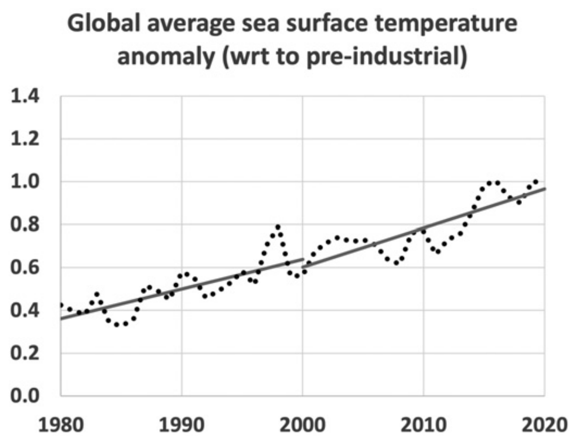

Figure 1.4 Ocean global warming with respect to the pre-industrial level. The dotted line shows the annual average anomalies of the sea-surface temperature, where the anomaly has been computed with respect to the pre-industrial level. The two straight lines show the best linear fit lines between 1980–2000 and 2000–2020. *Source*: Data from *Our World in Data*: https://ourworldindata.org.

It is interesting to compare global warming measured over land with that computed over sea. Figure 1.4 shows the equivalent of Figure 1.3, but for the global ocean. Note that in 2020 the global average sea-surface temperature was about one degree warmer than pre-industrial levels, up from about 0.4°C in 1980, and that the six years from 2015 to 2020 were also the six warmest years for the ocean since 1980. If we compare the warming trend of the two periods, 1980–2000 and 2000–2020, results (Table 1.1) indicate that it also increased, albeit by a smaller amount than on land surfaces, from 0.014°C per year (that is, 0.14°C every 10 years), to 0.018°C per year (0.18°C every 10 years).

Average global warming is not the only evidence that the climate is changing, as was summarized by the report by the Intergovernmental Panel on Climate Change (IPCC) published in August 2021, notably the Summary for Policy Makers (SPM) of the IPCC Working Group I.[5] The water cycle also intensifies, bringing with it in some regions more intense rainfall and flooding, as well as more intense drought in other regions. Concerning rainfall, precipitation has been concentrating in fewer, more intense events, especially at high latitudes. Some areas, such as the Mediterranean region, have seen, on average, a decrease in the average amount, and more frequent and longer dry periods.

Climate change-induced sea-level rise has been accelerating particularly in the past decade, with sea levels rising by an average of 3.4 mm per year, so much so that extreme sea-level events that previously occurred once in 100 years could conceivably happen every year by the end of the twenty-first century. Permafrost thawing, the loss of seasonal snow cover, the melting of glaciers and ice sheets, and a more substantial melting of Arctic sea ice (which is projected to be ice-free in summer before the end of the century) have also appeared more frequently. Climate change has also induced ocean warming, ocean acidification, and reduced oxygen levels, which have been affecting the ocean ecosystems.

For cities, some aspects of climate change have been amplified, including heat waves (as urban areas are usually warmer than their surroundings), flooding from heavy precipitation events, and sea-level rise in coastal areas.

Figure 1.5 shows how the Arctic sea-ice minimum extension has decreased from 1980 to 2020. It bears noting that in 2020, the minimum extension was about 50% smaller than the

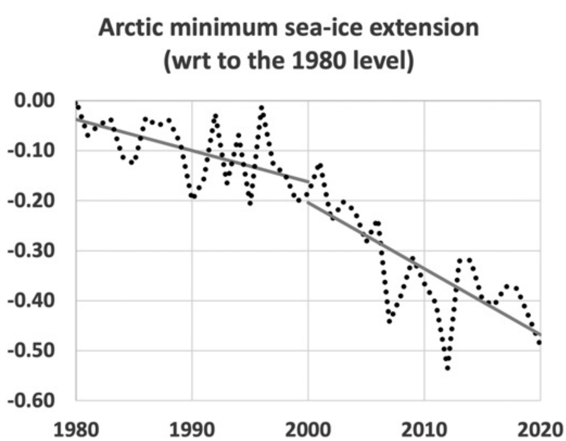

Figure 1.5 Arctic minimum sea-ice extension, compared to the 1980 level (in 1980, the minimum extension was about 7.7 million km^2; a value of –0.1 indicates that the minimum extension has decreased by 10%, to about 6.8 million km^2). The dotted line shows the annual average decrease of the minimum extension, computed with respect to the 1980 value. The two straight lines show the best linear fit lines between 1980–2000 and 2000–2020. *Source*: Data from *Our World in Data*: https://ourworldindata.org.

[5] Summary for Policymakers, in Masson-Delmotte et al., *Climate Change 2021: The Physical Science Basis.*

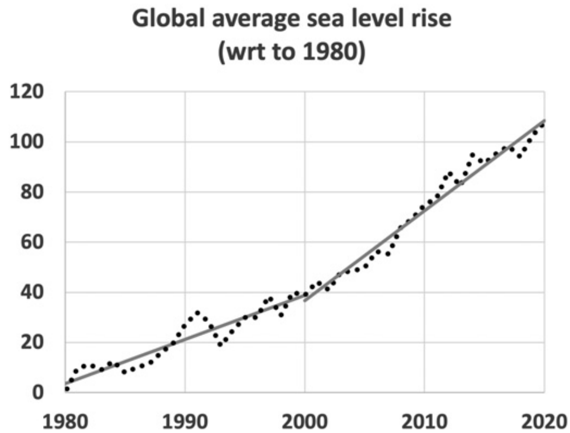

Figure 1.6 Sea-level rise, expressed in mm, compared to the 1980 level. The dotted line shows the annual average sea-level rise, computed based on the 1980 value. The two straight lines show the best linear fit lines between 1980–2000 and 2000–2020. *Source*: Data from *Our World in Data*: https://ourworldindata.org.

minimum extension in 1980. It also bears noting that, as was the case for the global average land and ocean temperatures, this melting trend has steadily increased in the last two decades as against the period between 1980 and 2000 (see also Table 1.1).

As a final piece of evidence, Figure 1.6 shows the global sea-level rise, with respect to the 1980 level. In 2020, the sea level was, on average, about 120 mm (12 cm) above the 1980 level. It is also noteworthy that, as was the case for the other three variables, the sea-level rise was occurring about two and a half times faster in the last two decades compared to the first two decades (Table 1.1).

Figures 1.3 to 1.6 and Table 1.1 indicate very clearly that global warming has been accelerating in the past two decades, which should not come as a surprise if we consider that, in these two decades, greenhouse gas emissions have been increasing faster than ever before (Figure 1.2).

The Working Group I (WGI) IPCC-SPM report also provides some updated estimates of the chances of crossing a global average warming level of 1.5°C and 2.0°C in the next decades. These global average limits were selected by the 196 countries that signed the Paris Agreement in 2015 as warming thresholds that should not be exceeded.[6] The WGI IPCC-SPM confirms that unless there are immediate and large-scale reductions in greenhouse gas emissions, limiting warming to 2.0°C will be beyond reach. Both the WGI IPCC-SPM report and the Copernicus Climate Change Service reported that without immediate and drastic reductions, the global average warming will be above the 1.5°C level in about 15 years (the exact year of crossing this level depends on future emissions).[7]

[6] United Nations Framework Convention on Climate Change, opened for signature 17 December 1994, entered into force 16 April 1998; Paris Agreement, opened for signature 22 April 2016, entered into force 4 November 2016.

[7] Temperature data taken from the European Union's Copernicus Climate Change Service, available at https://climate.copernicus.eu.

1.4 How Did We Get to This Point?

Greenhouse gas molecules, once injected into the atmosphere, are transported by the atmospheric flow globally, and remain there for a long time. For CO_2, current estimates suggest that they remain in the atmosphere for anywhere between 30 and 1,100 years, with the number of years depending on which removal processes are dominant. Methane (CH_4), by contrast, remains in the atmosphere for about 12 years, and is then removed by chemical reactions. Nitrous oxide (N_2O), another important greenhouse gas, remains in the atmosphere for about 150 years.

Let us suppose that today we decided to completely stop emitting greenhouse gases: how long would it take for the actual concentration to halve? The answer again depends on the greenhouse gas: for CO_2, the time to halve the concentration is about 120 years, for CH_4 it is about 10.5 years, and for N_2O it is about 132 years. This rather long lifetime (long with respect to human life) of greenhouse gases is the reason why the effects of human-induced emissions are (and will be) felt for many generations after they are injected into the atmosphere. It is also the reason why, to understand how we got to this situation, it is important to accumulate emissions over a long time, and analyse who has contributed most to the existing stock of greenhouse gases, and not limit ourselves to the most recent years.

Figure 1.7 shows the total and per-capita CO_2 emissions between 1990 and 2016. These two years have been selected because 1990 is often chosen as the reference with respect to what emission reduction targets are set, and 2016 because at the time of writing (2022) this is the last point available in the data archive we used in this work.[8] ‘Per capita’ values have been computed, year by year, by dividing the total emissions by each country/region population.

In terms of total emissions (Figure 1.7a), during the 1990–2016 period the United States, People’s Republic of China (hereafter indicated as PRC), Russia, Canada, Australia, India, and the European Union (EU) emitted about 68% of the world CO_2 emissions. The PRC and the United States contributed most: they emitted about 21% and 20%, respectively, of the CO_2 emissions injected into the atmosphere in those 26 years. They are followed by the EU, which injected about 12% of the total accumulated CO_2 emissions. The other major emitters followed these three, with contributions ranging from about 7% (Russian Federation) to 1% (Australia).

Let us now contrast the total emissions with the emissions per capita, because emissions per capita are considered a more ‘just’ measure as they reflect better whether each individual person has been given access to the same amount of energy. Energy that today, it is worth remembering, is still mostly produced (84%) using fossil fuels.

Figure 1.7b shows that one person living in the United States has emitted over 26 years some 500 tons of CO_2 in the period spanning 1990–2016, compared to about 120 tons for a person living in the PRC. Australia, Canada, and Russia now rank second, third, and fourth among the major emitters, respectively. Note that, for comparison, a person living in India has emitted only about 30 tons of CO_2 in that same 26-year period, about the same amount that persons living in the top four polluters injected into the atmosphere in only 2 years.

[8] Data from *Our World in Data*: https://ourworldindata.org.

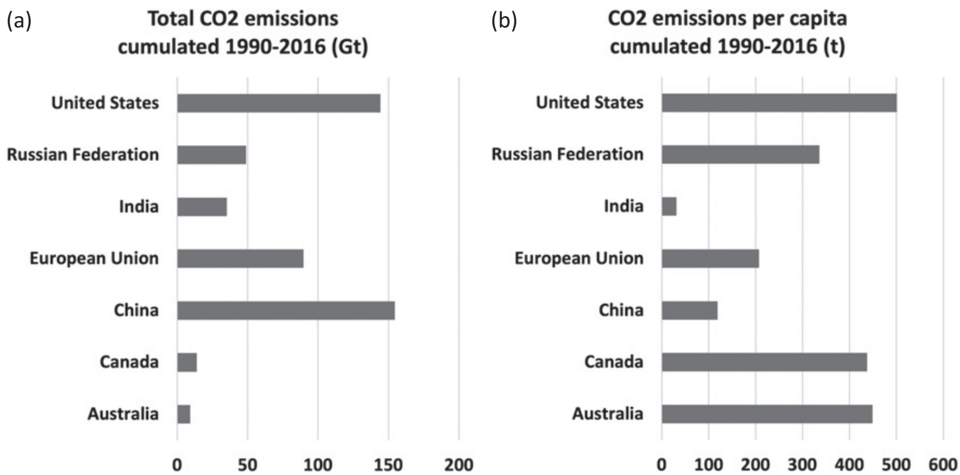

Figure 1.7 (a) Total CO_2 emissions accumulated between 1990 and 2016 by the seven major global emitters: the United States, Russia, India, European Union, the People's Republic of China, Canada, and Australia (values are expressed in gigatons, that is, 10^9 tons). (b) CO_2 emissions per capita accumulated between 1990 and 2016 by the seven major global emitters (in tons). *Source*: Data from *Our World in Data*: https://ourworldindata.org.

It is interesting to compare these numbers with the world average CO_2 emissions per capita over the same period, that is, 115 tons. Compared to this reference, a person living in the top four polluters emitted about four times more than the reference, a person living in the EU about two times more, a person living in the PRC the same as the average, and a person living in India one quarter, that is, four times less.

Figure 1.7 can help us to understand who has contributed more to the accumulation of greenhouse gases in the atmosphere, and thus to global warming. Clearly, as economies have developed and transformed throughout the years, the emission ranking has been changing. It is interesting to compare Figure 1.7 with the ranking of the last available year, 2016, shown in Figure 1.8.

Figure 1.8 indicates that in terms of total emissions, in 2016 the PRC was the top contributor with a contribution of about 29% to global emissions, followed by the United States with about 15% and the European Union with about 8.5%. If we look at per-capita emissions, in 2016 the United States, Canada, and Australia were the top polluters (as they were in terms of accumulated emissions between 1990 and 2016), with emissions per capita at about 15 tons, compared to about 7 tons for a person living in the PRC, 6.5 tons for a person living in the EU, and 1.8 tons for a person living in India. Note that in 2016, the world average CO_2 emission per capita was about 4.5 tons. On this footing, it is evident that even in the most recent past there have still been countries emitting about four times more than the average, and countries emitting about a quarter (that is four times less).

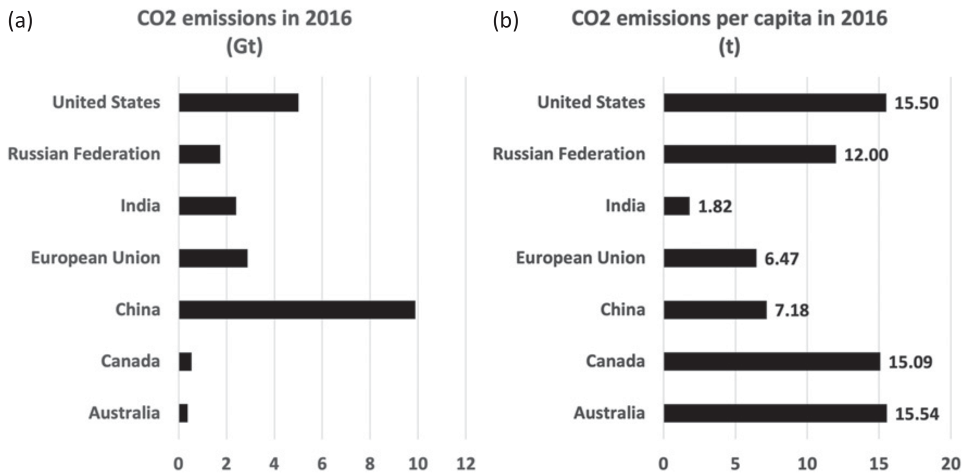

Figure 1.8 (a) Total CO_2 emissions in 2016 by the seven major global emitters: the United States, Russia, India, EU, the People's Republic of China, Canada, and Australia (values are expressed in gigatons, that is, 10^9 tons). (b) CO_2 emissions per capita in 2016 by the seven major global emitters (in tons). *Source*: The World Bank. Emissions data are sourced from Climate Watch Historical GHG Emissions (1990–2020). 2023. World Resources Institute. Available online at: climatewatchdata.org/ghg-emissions. Data source: World Development Indicators. https://data.worldbank.org/indicator/EN.ATM.CO2E.PC

1.5 The Link between Greenhouse Gases and Global Warming

The WGI IPCC-SPM report on the physical basis of climate change published in August 2021 talks about a quasi-linear relationship between the amount of greenhouse gases that are emitted in the atmosphere and global warming.[9] Indeed, if we contrast global warming, measured by the global annual average surface temperature anomaly from 1980 to date against greenhouse gases accumulated since 1980, we can detect a quasi-linear trend.

The best-fit straight line shown in Figure 1.9 has a slope of 0.5°C per 1,000 gigatons, which means that during this period, an accumulation of 1,000 gigatons of greenhouse gases explains 0.5°C of warming. The coefficient of determination of the linear fit, $r^2 = 0.82$, confirms the existence of a robust linear relationship. The correlation is not perfect (that is, 82% instead of 100%) because there are variations around this linear relationship, which reflect the fact that each year's climate is influenced not only by greenhouse gas concentration, but also by the atmosphere and ocean internal dynamics (such as whether the year was characterized by a strong El Niño or La Niña event, or whether other changes in the large-scale circulation caused heat waves over large areas of the globe). Note that the slope of 0.5°C per 1,000 gigatons found in our data analysis is very close to the slope of about 0.45°C per 1,000 gigatons reported in the WGI IPCC-SPM.

9 Summary for Policymakers, in Masson-Delmotte et al., *Climate Change 2021: The Physical Science Basis.*

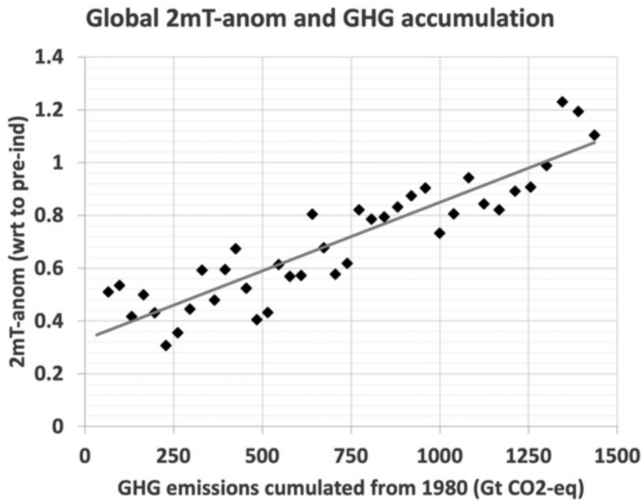

Figure 1.9 Total accumulated greenhouse gases from 1980 (*x*-axis; *source*: data from *Our World in Data*: https://ourworldindata.org) versus global annual average surface temperature anomaly with respect to the pre-industrial level (*y*-axis; *source*: generated using Copernicus Climate Change Service information (2022) available at https://climate.copernicus.eu).

We can use this quasi-liner relationship to estimate the maximum we could emit if we wanted to limit warming below 2.0°C. Given that in 2020 the global average warming was about 1.2°C, if we assume a slope of 0.45°C per 1,000 gigatons, we can only emit about 1,800 gigatons of greenhouse gases. Note that in 2019, we (that is, the global population) emitted about 45 gigatons of greenhouse gases (of which roughly 30 gigatons comprised CO_2 and roughly 15 gigatons comprised CH_4 and other greenhouse gases). If in the next decades we continue to emit, on average, about 45 gigatons per year, in about 40 years we would inject 1,800 gigatons of greenhouse gases into the atmosphere, and global warming would very likely be above 2.0°C.

If, instead, we want to keep global warming below 1.5°C, we have to limit the emissions to less than about 670 gigatons. If we continue to emit as we did in 2019, that is about 45 gigatons per year, we will surpass that value in about 15 years.

1.6 Concluding Remarks

We started our discussion, in the introduction, by remembering what the greenhouse effect is, and its key role in allowing the development of complex life forms over Planet Earth. Then, in the first section, we discussed the observed, continued increase in the concentration of greenhouse gases in the atmosphere; an increase that is mainly due to human activities, as stated very clearly in the WGI IPCC-SPM report published in August 2021:[10] 'It is

[10] Summary for Policymakers, in Masson-Delmotte et al., *Climate Change 2021: The Physical Science Basis.*

unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred' (see also the WGI IPCC-SPM at Figure 1.1). This has been confirmed by the latest IPCC report on climate change mitigation, released in April 2022 by the IPCC Working Group III.[11] These two, together with the IPCC Working Group II report on impacts, adaptation, and vulnerability, provide one of the most reliable, authoritative, and up-to-date summaries of the state of the climate and of our knowledge on how it will very likely evolve in the forthcoming years.[12]

In the second section, we documented the impact of the continued increase in greenhouse gas concentration on a few key climate variables between 1980 and 2020, and we also briefly documented the uncontroversial impacts of climate change on the Arctic sea-ice extension and the global average sea level. By comparing linear trends between two 20-year periods, 1980–2000 and 2000–2020, we have highlighted how many physical variables confirm that climate change has been accelerating.

In the third section, we discussed how humanity reached this point, and analysed emissions accumulated over a 26-year period between 1990 and 2016. We have compared total country emissions to per-capita emissions, showing that according to this latter measure the ranking sees the United States as the top contributor to climate change, followed by Australia, Canada, the Russian Federation, the EU, and then the PRC.

In the fourth section, we discussed a quasi-linear relationship between the amount of greenhouse gases accumulated in the atmosphere and global warming. This relationship, which is pointed out explicitly in the 2021 WGI IPCC-SPM report, shows that an accumulation of another 1,000 gigatons of greenhouse gases would lead to a 0.45°C warming. This relationship can be used as a simple, back-of-the-envelope estimate of the future climate. If this is applied, considering that in 2019 the global population injected into the atmosphere about 45 gigatons of greenhouse gases, and assuming that emissions will continue at this level, on average, for the next decades, we can predict that in about 15 years the global average warming will be about 1.5°C. We can also predict that in about 40 years the global average warming will be at about 2.0°C.

Therefore, it should be clear both what has been happening to the climate, and why it is necessary to start immediately to reduce the emission of greenhouse gases in a substantial way. If we want to keep the average global warming below 1.5°C or 2.0°C (these being the two targets agreed at the United Nations Framework Convention on Climate Change Conference of the Parties (COP) meeting in 2015), we need to start substantially reducing emissions immediately, on average by at least 5% per year, until we reach zero net emissions in 2050.

We can apply the simple quasi-linear relation between accumulated greenhouse gases and global average warming to look ahead. If we analyse the emissions during the last

[11] H. O. Pörtner, D. C. Roberts, M. Tignor, et al. (eds.), *Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2022).

[12] P. R. Shukla, J. Skea, R. Slade, et al. (eds.), *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC, 2022).

decade, they grew from nearly 40 gigatons in 2009 to nearly 46 gigatons in 2018 (data from The World Bank database: https://data.worldbank.org), and thus by about 1% annually. The diamonds in Figure 1.10 show the amount of greenhouse gases accumulated in the atmosphere and projected warming in 2050 computed by applying the quasi-linear relationship discussed above, under four emission scenarios:

- A continued average *increase* of 1% per year, as was the case in 2009–2018: this will cause a further 1,738 gigatons of greenhouse gases to be injected into the atmosphere, which will reach 3,173 gigatons in 2050, and a warming of 2.0°C by 2050.
- A continued average *decrease* of 1% per year, starting in 2019: this will cause a further 1,249 gigatons of greenhouse gases to be injected into the atmosphere, which will reach 2,684 gigatons in 2050, and a warming of 1.75°C by 2050.
- A continued average *decrease* of 3% per year, starting in 2019: this will cause a further 994 gigatons of greenhouse gases to be injected into the atmosphere, which will reach 2,429 gigatons in 2050, and a warming of 1.61°C by 2050.
- A continued average *decrease* of 5% per year, starting in 2019: this will cause a further 703 gigatons of greenhouse gases to be injected into the atmosphere, which will reach 2,138 gigatons in 2050, and a warming of 1.47°C by 2050.

This rather crude and simple prediction confirms results obtained with more complex Earth-system models: only by decreasing the emissions on average by 5% every year can we

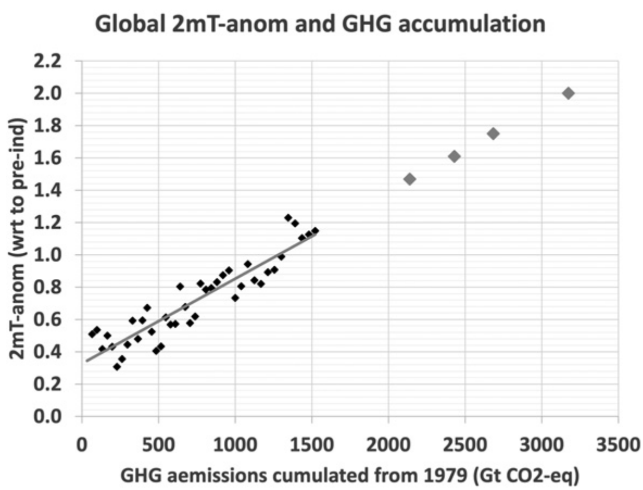

Figure 1.10 As Figure 1.9 (up to accumulated emissions of about 1,500 gigatons (dots)), adding projections of the state of the climate in 2050 in four emission scenarios (diamonds; see text for details). *Source*: Generated using Copernicus Climate Change Service information (2022) available at https://climate.copernicus.eu.

limit the global average warming to below 1.5°C. However, it is worth mentioning that even in this scenario, in 2050 we will still be injecting about 9 gigatons of greenhouse gases into the atmosphere. If we want to achieve net zero emissions, a target often discussed by the EU, we must reduce emissions, on average, by at least 8% every year. In fact, an average annual reduction of 8% per year would lower emissions from 45 gigatons emitted in 2019 to about 3 gigatons by 2050, a value much closer to zero.