The Physical Basis for Climate Change

Desmond Leddin

Abstract The purpose of this chapter is to review the scientific background to the issue of global warming and climate change. This chapter starts by presenting the history of atmospheric science and the basis of how greenhouse gases (GHGs) contribute to atmospheric warming. It is important to understand the sources of greenhouse gases, their mechanism of action, relative contributions to warming, and the contributions of different countries to the problem to help the global efforts in mitigation and adaptation of the impacts of climate change. Future projections for climate including temperature, precipitation, drought, and extreme weather events such as cyclones are addressed. This chapter explains briefly the computer-based models used to study the projected climate changes in different scenarios in different regions of the world.

Global initiatives to reduce greenhouse gases will be discussed. At present, it is not clear whether that effort will be sufficient to keep global mean surface temperature (GMST) below 2 °C by the end of the century as set under the Paris Agreement. Given that expectation, it is important that countries begin to adapt to the new climate realities and prepare for the changes that are coming. This is especially important in Africa where a significant vulnerable population will face increasing challenges of changes in temperature, precipitation, and access to water and nutrition, which impact the infrastructure and the socioeconomic stability of vulnerable countries.

Keywords Climate change · Africa · Global warming · Precipitation · Drought · Extreme weather events · Climate change models

D. Leddin (✉)
Department of Medicine, Dalhousie University, Halifax, NS, Canada
e-mail: desmond.leddin@dal.ca

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Abbreviations

AR6	Assessment Report 6
COP	Conference of the Parties
EPA	Environmental Protection Agency
GHG	Greenhouse gases
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
NDC	Nationally determined contributions
PPM	Parts per million
RCP	Representative concentration pathways
SSP	Shared socioeconomic pathways
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change

1 Introduction

The purpose of this chapter is to review the scientific background to the issue of global warming and climate change. The history of atmospheric science and the recognition of how greenhouse gases contribute to atmospheric warming will be briefly reviewed. It is important to understand the sources of greenhouse gases, their mechanism of action, relative contributions to warming, and the contributions of different countries to the problem. The response to the threat will be discussed as will the projections for future warming and the consequences that will ensue.

2 Historical Background

The atmosphere that surrounds the Earth is of fundamental importance to life on the planet. Changes in the atmosphere as evidenced by changes in weather, precipitation, and temperature affect our daily life and our ability to access the basic necessities of shelter, water, and nutrition.

Evidence of attempts to understand changes in the atmosphere goes back as far as recorded history. Both the ancient Egyptian and Greek scholars attempted to study, understand, and predict atmospheric conditions (Zinezer 1944; Clark 2022). In more modern times, the work of the French scientist Joseph Fourier (1768–1830) is foundational to understanding the role of the atmosphere in global warming. Fourier calculated that the earth, given its distance from the sun, should be much colder than it is and postulated that the atmosphere was acting as an insulator. In the mid-nineteenth century, as the understanding of geology continued to advance, there was a considerable interest in how glaciers advanced and retreated. Driven in part by a desire to understand that cycle, the American amateur scientist Eunice Foote and the Irish scientist John Tyndall studied the role of different gases in producing the insulating effect of the atmosphere. In 1896, the Swedish scientist Svante Arrhenius published his work on the mathematics of atmospheric warming and the role that carbon dioxide (CO_2) might play (Arrhenius 1896). Although both Foote and Arrhenius clearly pointed out the potential for increased atmospheric carbon dioxide to increase global temperature, this was not perceived as a threat. It was thought that a warming climate would lead to a greater opportunity to grow crops and would generally be a positive effect.

Weart (2004) described how gradually through the twentieth century came the realization that atmospheric warming could have negative consequences. This came prominently to public consciousness with the testimony of the scientist James Hansen to Congress in 1988. Hansen's testimony was based in part on the data and measurement of carbon dioxide in the atmosphere from the laboratory of Charles Keeling (1928–2005). Keeling had established the laboratory at the summit of an extinct volcano in Hawaii. He showed that carbon dioxide levels were rising inexorably over the time span of his measurement. In the same year as Hansen's presentation, the United Nations established the Intergovernmental Panel on Climate Change (IPCC), which has become a major force in bringing science of climate change to both public and politicians.

The industrial revolution began in the mid-eighteenth century. It was characterized by a switch in manufacturing processes from hand production to machine production. It began first in the United Kingdom and Europe and somewhat later in the United States. Some countries have only industrialized in relatively recent times. The switch to machine manufacturing requires energy. Initially, some of this was provided by waterpower, but later it depended on the combustion of fossil fuels, particularly coal, oil, and gas. Coal has been mined in ancient times in China and during the Roman Empire. However, this was on a small scale, and it was only with the advent of the industrial revolution that coal mining could be and was carried out in industrial quantities. Mining of coal, a very potent source of greenhouse gases and aerosol emissions, continues to the present. Some of the world's greatest producers and consumers of coal are among those countries with the highest greenhouse gas emissions per capita. Coal is an important source both of energy and of greenhouse gas emissions and pollution. The history of the oil industry is similar. Oil extraction did exist in China over 1500 years ago, but it was only in the mid-nineteenth century that commercial development really expanded. Oil overtook coal as the world's main source of energy from the mid-1900s on.

3 Greenhouse Gases

How do they cause warming? When solar radiation strikes the surface of the earth, or the atmosphere, some is reflected but most is absorbed and causes heating. The heat is reflected from the surface of the warmed earth and atmosphere in the infrared

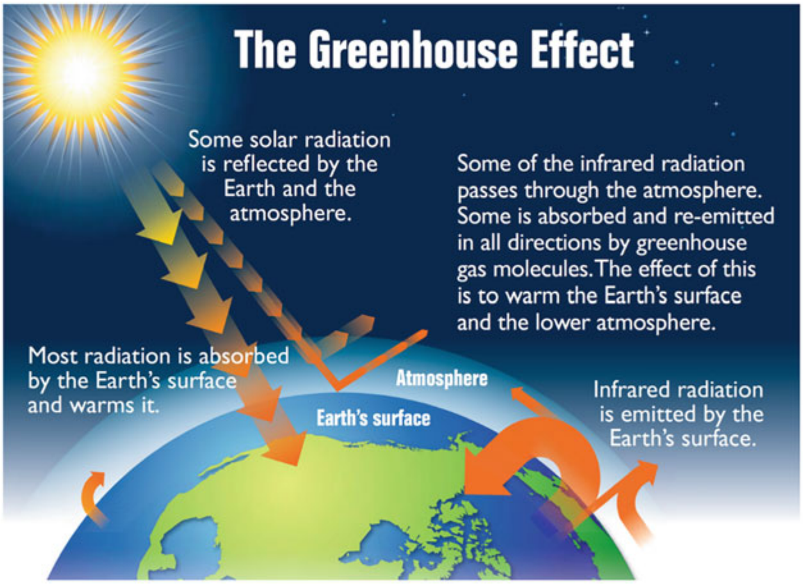

Fig. 1 The greenhouse effect. (Source: US EPA 2012)

spectrum, a different wavelength to that of the solar energy coming in. Infrared radiation travels at a wavelength of 700–1,000,000 nm. Oxygen and nitrogen do not absorb radiation at this wavelength, but some atmospheric gases such as carbon dioxide do. This leads to increased kinetic energy of the molecules in these gases, which effectively then act as storage for heat that would otherwise be lost into space (Fecht 2021). Although this is described as the greenhouse effect, it is not how greenhouses warm air. Greenhouses work by trapping heated air that is not allowed to move away by convection and other forces (Fig. 1).

4 Origins and Impacts

The main greenhouse gases in the earth's atmosphere are water vapor, carbon dioxide, methane, nitrous oxide, and ozone. Although water molecules persist in the atmosphere for a very short duration, they are an important source of warming and an example of a positive feedback loop. Warmer temperatures cause more evaporation of water from the surface of the earth and oceans, and this leads to further warming of the atmosphere.

The gases differ in their origins, the degree to which they contribute to warming and in their duration of action in the atmosphere. The relative contribution, the global warming potential (GWP), of each gas is calculated relative to that of carbon dioxide, which is given a reference value of 1 as mentioned in the Environmental

Protection Agency (EPA) website (https://www.epa.gov/ghgemissions/understanding-global-warming-potentials).

The following is from an overview of greenhouse gases (EPA n.d-a). Carbon dioxide is the most abundant greenhouse gas comprising about 80% of greenhouse gas emissions in the United States. It is released into the atmosphere primarily through burning of fossil fuels such as coal, natural gas oil, and gasoline. It can also be generated by burning solid waste, wood, and other biological materials including biofuels. Significant amounts are released through the production of cement and other chemical reactions. Carbon dioxide undergoes a carbon cycle. When it is released into the atmosphere, it is absorbed by the oceans, soil, and plants; incorporated into organic materials; and released again (EPA n.d-b).

Methane, which comprises about 10% of the US emissions, is present in much smaller amounts than carbon dioxide but is much more potent as a greenhouse gas. It has a GWP of 28–36. Methane lasts for a much shorter period in the atmosphere than carbon dioxide but because of its molecular structure it can absorb more reflected infrared energy. The primary sources of methane are the fossil fuel industries as considerable amounts of methane are leaked during the production of natural gas and during the production and transport of coal and oil. Cattle are also an important source as ruminants belch methane into the atmosphere as part of their digestive process. Methane also arises from the decay of organic matter, which can be naturally occurring or can occur from landfills.

Nitrous oxide, 3% of emissions, has a GWP of 265–298 times that of carbon dioxide. This gas can be generated by the combustion of fossil fuels and solid waste and during the treatment of wastewater. Agricultural land use and industrial activities contribute significant amounts.

Chlorofluorocarbons, hydrofluorocarbons, hydrochlorofluorocarbons, perfluorocarbons, and sulfur hexafluoride, although present in small amounts (3%), are much more powerful than any of the other gases with GWPs of thousands to tens of thousands. They are emitted from a variety of industrial processes. Fluorinated gases are sometimes used as substitutes for ozone-depleting chemicals. Some anesthetic gases are chlorofluorocarbons and a significant contributor to atmospheric warming (Charlesworth and Swinton 2017).

Ozone is technically a greenhouse gas but is often not considered as such. Its role in global warming and environmental protection is complex depending on its concentrations of different levels of the atmosphere. In the troposphere, where humans live, it can be injurious to health. Ozone is created by a chemical reaction between sunlight, nitrogen oxides, and volatile organic compounds. The main sources are emissions from cars, power plants, and industrial and commercial activities. In the stratosphere, it prevents harmful ultraviolet radiation from reaching the surface of the earth and is a benefit to humans and plants.

5 Global Production and National Contributions

Historical measurements of carbon dioxide are available from ice core measurements and from current real-time monitoring. Over the last several hundred thousand years, carbon dioxide levels have fluctuated but have never exceeded 300 parts per million (ppm) until the onset of industrialization. Atmospheric carbon dioxide concentrations are now higher than at any time in at least two million years, and concentrations of methane and nitrous oxide are higher than at any time in the last 800,000 years (IPCC AR6 WGI SPM A 2.1 n.d.).

Once coal, and later oil, began to be used as an energy source, carbon dioxide levels began to rise very quickly and now exceed 415 ppm. The onset of industrialization also coincided with rapid increases in human populations. The combination of rising numbers of people utilizing increasing amounts of fossil fuels to drive economic growth has led to the increase in atmospheric carbon, which is now seen. In 1922, total global carbon dioxide emissions were 3.23 billion tonnes. The current production of carbon dioxide is over 36 billion tonnes (Our World in Data n.d.-b), and total GHG approximates 50 billion tonnes per year of CO_2 equivalents. In the last 100 years, there has been an increase in emissions of over 1500%.

6 Sources of Emissions

Energy production accounts for nearly three quarters of global greenhouse gas emissions. Given the central role of fossil fuels in the global economy, this is not surprising. This includes energy used in buildings (17.5%), transportation (16.2%), and industry (24.2%). Agriculture, forestry, and land use contribute 18.4%, waste 3.2%, and industrial processes involved in chemical and cement manufacturing 3%. The type of greenhouse gas produced varies by economic sector. For example, fugitive emissions from energy production account for nearly 6% of greenhouse gases. The greenhouse gas in this case is predominantly methane. Cement and steel are essential building materials and are a particular concern. It has been estimated that cement contributes 2,300,000,000 tonnes of carbon dioxide per year to global emissions. Making iron and steel contributes 2,600,000,000 tonnes (Fennell et al. 2022) (Fig. 2).

Knowing the origin of the gases within each sector is important for mitigation efforts. Within the agricultural sector, for example, cattle are the leading producer of greenhouse gases. They produce up to hundred kilograms of methane per year. This has led to calls to move away from a meat-based diet toward one higher in vegetables and associated with lower emissions.

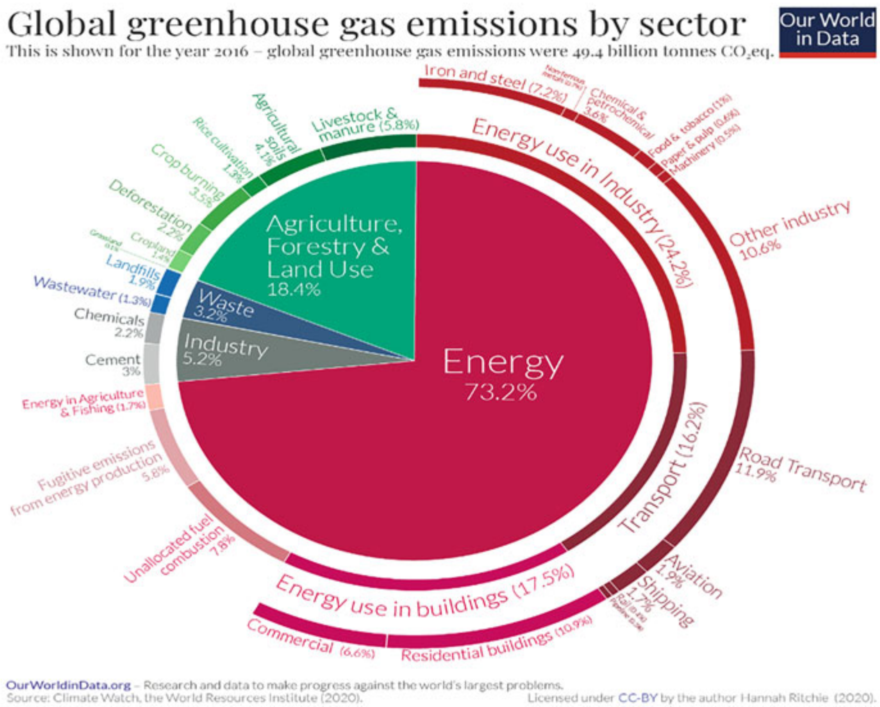

Fig. 2 Global greenhouse gas emissions by sector. (Source: Our World in Data n.d.-a. OurWorldinData.Org – Research and data to make progress against the world's largest problems. Source: Climate Watch, the World Resources Institute (2020). Licensed under CC-BY by the author Hannah Ritchie 2020)

7 Health Sector Contributions

The National Health Service in the United Kingdom has published an analysis of its carbon footprint (Tennison et al. 2021).

The largest single component in the UK health system is the supply chain and the goods and services required to deliver the service. Pharmaceuticals and chemicals are the largest components of this with medical equipment and business services coming in close behind. Delivery of care requiring use of building energy, and generating waste, and business travel are the next largest sectors followed by personal travel, which includes patients, staff, and visitors.

8 Which Countries Contribute the Most?

There are differences between continents with regard to CO_2 production. The most is produced in Asia with North America and Europe also producing large amounts. Africa, one of the continents that are most likely to suffer from climate change, produces relatively little, as does South America and Oceania (Fig. 3).

Countries with large populations and a large industrial base are the greatest contributors. In absolute terms of emissions per country, the pattern is somewhat different. China, because of its large population and rapid industrialization, is the world's largest emitter of greenhouse gases with annual CO_2 emissions from fossil

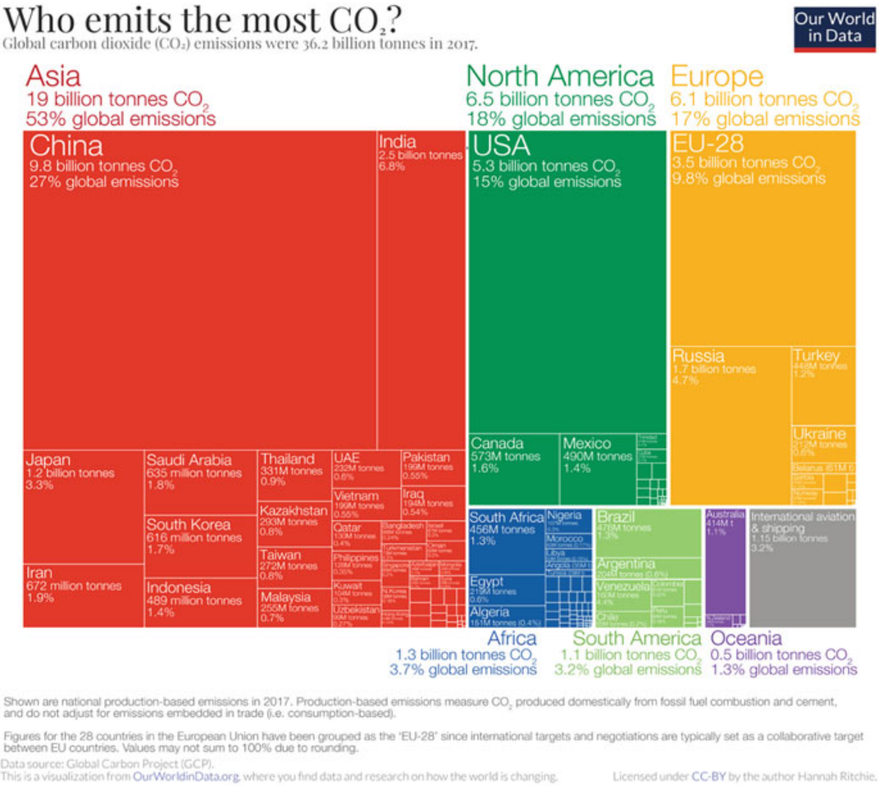

Fig. 3 Carbon dioxide emissions by continent and country. The size of the block is proportional to the amount of emissions. (Source: Our World in Data n.d.-c. Shown are national production-based emissions in 2017. Production-based emissions measure CO_2 produced domestically from fossil fuel combustion and cement, and do not adjust for emissions embedded in trade (i.e. consumption-based). Figures for the 28 countries in the European Union have been grouped as the 'EU-28' since international targets and negotiations are typically set as a collaborative target between EU countries. Values may not sum to 100% due to rounding. Data Source: Global Carbon Project (GCP). This is a visualization from OurWorldinData.org. where you find data and research on how the world is changing. Licensed under CC-BY by the author Hannah Ritchie)

fuels of around ten billion tonnes. The United States is just about a half of this at 5.26 billion tonnes, and the 27 European Union states reduce 2.91 billion tonnes. India, again because of its large population and rising industrialization, is a significant contributor at 2.63 billion tonnes.

In per capita terms, in 2019, the average emissions in the world were 4.76 tonnes. Australia (16.45 tonnes per person), the United States (15.97 tonnes), and Canada (15.57 tonnes) are the world's largest emitters significantly exceeding those of China at 7.32 tonnes per person and even those of the industrialized United Kingdom at 5.46 tonnes per person.

9 Pollution

Pollution is the introduction into the environment of substances that cause damage to the human or natural environment. Pollutants can be naturally occurring or synthetic and be composed of solid, liquid, gas, or simply energy such as light and radiation. Pollutants can affect humans and the environment either directly or indirectly. Some pollutants are directly toxic, and others act by affecting water and air quality or enter the food chain.

Pollution and climate change interact in several ways. The same factors that drive global warming and climate change also contribute to pollution of the environment. Combustion of fossil fuels, one of the main drivers of global warming, by cars is a very significant contributor to air pollution and climate warming. Another example is the relationship between climate change and wildfires. Climate change may lead to an increase in the number of wildfires. Wildfires, in turn, release significant pollutants into the atmosphere. Furthermore, the chemicals used to stop wildfires can get into the water reservoirs and pollute rivers and soil.

In the context of climate change, much attention is focused on the role that aerosols might play in global warming or cooling. Aerosols in the atmosphere can be suspensions of liquid, solid, or mixed particles (Myhre et al. 2013). They vary in chemical composition and size (Putaud et al. 2010). They can be either primary aerosol, those released into the atmosphere, or secondary aerosol, those produced in the atmosphere from precursor gases. Primary aerosols can be organic or inorganic. Some aerosols can absorb solar radiation and contribute to global warming. Black carbon is the most important of these. Others can scatter solar radiation and have a cooling effect. Since burning of fossil fuels is an important source of aerosols, a reduction in aerosol concentration in the atmosphere, as attempts are made to reduce fossil fuel consumption, may paradoxically remove the beneficial cooling effect of these aerosols.

10 Biodiversity

Biodiversity can be defined as the biological variety and variability of life on the earth. Biodiversity is essential for healthy human and planetary systems (Cardinale et al. 2012) including food production, water cleansing, and prevention of zoonoses. Biodiversity loss is related to climate change and pollution in that some of the same factors that are contributing to climate change and damage to the environment can also cause loss of biodiversity. For example, deforestation of the Amazon results in a shrinking habitat for plants and animals. The land that is cleared may be used for rearing cattle, which in turn are a significant source of greenhouse gases. Similarly, the reef systems of the oceans, an important source of marine biodiversity, are vulnerable to changes in both the temperature and acidity. A lack of biodiversity may decrease the stability and productivity of ecosystems and increase vulnerability to infections that can affect humans, animals, and flora.

11 The Response to the Climate Crisis

The Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organization and the United Nations in 1988 (IPCC; https://www.ipcc.ch). The mission of the IPCC is to produce reports on the natural, political, and economic impacts and risks and possible responses based on ongoing surveys of the world's literature. The IPCC does not conduct original research, but it does facilitate original work by bringing together hundreds of scientists.

Three working groups contribute to each of the IPCC reports, which are now in the sixth cycle. Working Group 1 deals with the physical science basis; Working Group II deals with impacts, adaptation, and vulnerability; and Working Group III deals with the mitigation of climate change. The IPCC reports are an invaluable synthesis of current understanding of the challenge of climate change.

The United Nations Framework Convention on Climate Change (UNFCCC) entered into force in 1994. The goal of the treaty is to stabilize greenhouse gas concentrations. It arose in part from the Rio conventions in 1992 (United Nations Climate Change; https://unfccc.int). The UNFCCC was responsible for the Kyoto Protocol that was superseded by the Paris Agreement in 2016. The goal of the Paris Agreement was to keep global warming to below 2 °C by 2100. In order to meet that target, countries need to cut their greenhouse gas emissions. Each country has been asked to draw up nationally determined contributions (NDCs). The NDCs (Nationally Determined Contributions; United Nations Climate Change; https://unfccc.int) are nonbinding goals set by each country to mitigate climate emissions. The hope is that countries will cooperate globally to reduce emissions and limit atmospheric warming. Parties to the UNFCCC meet yearly at a Conference of the Parties (COP) to assess the progress toward meeting the goals of the convention.

Two issues arise. The first is whether the indices are sufficient to meet the target of the Paris Agreement, and the second is whether countries are meeting their targets. In a recent analysis, it has been found that the probability of the United States reaching its NDC was only 2% and it was 16% for China. Even if, as seems unlikely, countries do meet their NDCs, there is no certainty that atmospheric warming will stay under 2 °C. Based on the current trends, it has been reported that the probability of staying below 2 °C is only 5% (Liu and Raftery 2021). It is likely that by 2100 global mean surface temperature will exceed 2 °C.

11.1 Where Are We Now?

In October 2021, the IPCC Working Group I produced Assessment Report 6 (AR6) on the basis of physical science for climate change (IPCC 2021). The report stated that it was unequivocal that human influence has warmed the atmosphere, ocean, and land. This was an important development. Previously, the slight uncertainty as to the relative contributions of natural and human factors had allowed a basis for inaction on the part of some individuals and countries.

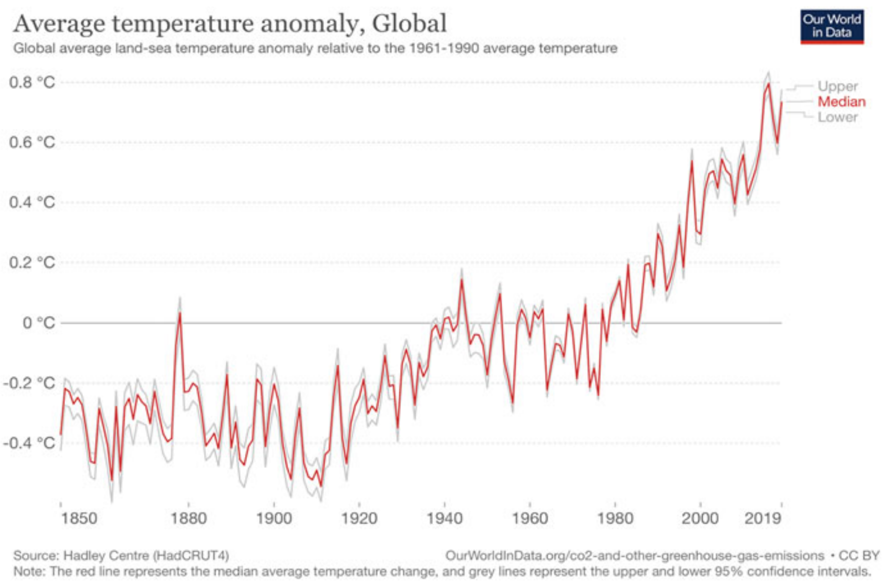

Fig. 4 Changes in global surface temperature since 1850. (Source: Our World in Data. https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions. Source: Hadley Centre (HadCRUT4). OurWorldInData.org/co2-and-other-greenhouse-gas-emisions. CC BY. Note: The red line represents the median average temperature change, and grey lines represent the upper and lower 95% confidence intervals)

As shown in Fig. 4, the world is now warmer than it has been anytime in the last 200 years. The rise in the temperature is unprecedented. While it is true that the world has been warmer than this previously, this has not occurred when humans inhabited the earth. Almost all, if not all, of the rising global mean surface temperature is due to human factors. The world has already warmed by over 1 °C compared with the preindustrial times (IPCC 2021).

A rise in global mean surface temperature has already resulted in changes in multiple interlinked systems. A warmer atmosphere can hold more water and contains more energy. AR6 concluded that human-induced climate change is already affecting weather extremes in every region across the globe (IPCC 2022). This is manifested by changes in climate extremes such as heat waves, heavy rainfall events, droughts, and tropical cyclones. The IPCC reported that heat extremes including heat waves have become more frequent and more intense, while cold extremes become less frequent and less severe. A decrease in cold extremes may seem like a benefit but that may not necessarily be so. Cold temperatures are important in controlling potential human and plant pathogens.

Consistent with the observation that a warmer atmosphere holds more water, the frequency and intensity of heavy precipitation events have increased since the 1950s over the most land areas. It was previously recognized that the intensity of storms has increased, but there is less certainty that the frequency may have increased.

Compound events are those in which several climate hazards combine (Zscheischler et al. 2018a, b). For example, drought associated with high heat may lead to wildfires and increased air pollution (Zscheischler et al. 2018a, b). The IPCC also reported that climate change has likely increased the chance of compound extreme events (IPCC 2022).

11.2 What Will Happen? Predicting the Future

Experiments cannot be carried out on the planet, so models are needed. Datasets allow different groups to have a common starting point for inputs into climate models. Perturbations can be introduced, and effects can be seen. Modelling changes in global temperature and the resulting climate over a period of decades are extraordinarily complex. It was not really possible before the advent of powerful computers. Even with modern computing technology, it remains a challenge. In order to facilitate the modelling process, datasets called Representative Concentration Pathways (RCPs) have been developed, which can be used to prime-modelling data (van Vuuren et al. 2011). RCPs were introduced beginning with IPCC Assessment Report 5. Variables such as population, land use, energy intensity, energy use, and regional differential development were incorporated.

Pathways were described based on the amount of change in radiative forcing by 2100. Radiative forcing is defined as the difference between the sunlight radiant energy received by the earth and the energy radiated back to space. RCP2.6 represents a peak in radiative forcing at approximately 3 W/m^2 during the mid-century before declining to 2.6 W/m^2 by 2100. RCP4.5 represents stabilization (without overshoot) in radiative forcing at 4.5 W/m^2 post-2100. RCP6.0 represents stabilization (without overshoot) in radiative forcing at 6 W/m^2 post-2100. RCP8.5 represents a rise in radiative forcing to 8.5 W/m^2 in 2100. RCP8.5 is often referred to as the business-as-usual scenario. It is the likely outcome if difficult, and immediate, mitigation efforts are not taken (RCPs n.d.).

Assessment Report 6 introduced Shared Socioeconomic Pathways (SSPs) (O'Neill et al. 2014). Socioeconomic narratives were not included in the RCPs, but the SSPs are based on five potential socioeconomic trends: SSP1, a world of sustainability-focused growth and equality; SSP2, a world where trends broadly follow their historical patterns; SSP3, a fragmented world of "resurgent nationalism"; SSP4, a world of ever-increasing inequality; and SSP5, a world of a rapid and an unconstrained growth in economic output and energy use (Carbon brief n.d.). As with RCP modelling, these new pathways include scenarios with high and very high greenhouse gas emissions, scenarios with intermediate greenhouse gas emissions, and scenarios with very low and low greenhouse gas emissions.

11.3 Consequences of Atmospheric Warming

The essential problem is a net positive increase in atmospheric energy due to the effect of greenhouse gases in the atmosphere. The primary effect of this energy is to increase atmospheric and global mean surface temperature. AR6 has modelled the temperature changes that may be seen with different climate scenarios varying from low-emission scenarios to high-emission scenarios.

11.3.1 Temperature

AR6 reported (IPCC 2022: AR6. SPM WGII B1.1. Table SPM 1) that global surface temperature will continue to increase until at least the mid-century under all the emission scenarios. In the near term, under all scenarios, the best estimate of temperature rise is 1.5 °C. Beyond 2040, however, temperature estimates begin to diverge based on the amount of net energy being retained in the atmosphere. Under the best case scenarios, temperature may reach 1.6 °C, but at the other end of the scale, with a high-emission scenario, it may reach as much as 2.4 °C.

This divergence is even more marked from 2081 on. In the long term, under a low-emission scenario, temperature rise may be held at 1.4 °C, but under a high-emission scenario, it will reach as much as 4.4 °C, with a very likely range of up to 5.7 °C.

The data emphasize the fact that we are in the critical decades with regard to controlling the magnitude of the rise of atmospheric temperature.

Increased temperature in the atmosphere affects wind patterns, the distribution of the amount of precipitation, the frequency and severity of storms, the frequency and intensity of high temperature events, the number of frost-free days, the temperature of the oceans, and melting of ice and permafrost.

When these changes are presented as averages, it is easy to lose the impact of extremes or of increasing variability in climate. For example, the average precipitation in an area may remain constant, but that is not helpful if the rain does not appear at the right time for planting or nurturing crops. A long period of drought followed by torrential rain may, on average, produce a normal amount of rainfall over the course of 12 months, but in fact it may be very destructive.

AR6 also reported that many changes in the climate system will become magnified in direct relation to an increase in global warming. Increases in the frequency and intensity of heat extremes, marine heat waves, heavy precipitation, in some regions drought, an increase in intense tropical cyclones, and reduction in Arctic ice and permafrost can all be expected (IPCC 2022: AR6 SPM WGII B2). It is also anticipated that there will be increased variability of the global warming, water cycle, global monsoon precipitation, and severity of wet and dry events. Thus far, the oceans have helped modulate the rise in atmospheric carbon and the rise in atmospheric temperature, but there are signs that the ability of the oceans to do this is beginning to be exhausted.

11.3.2 Oceans

Over 70% of the world's surface area is covered by oceans. Oceans contain 97% of the earth's water. An additional 10% of the earth's surface is covered by glaciers and ice sheets. The IPCC has produced a special report on the oceans and cryosphere. The oceans play a critical role in climate control but are also important as a source of food and for trade, transport, and habitat. The IPCC estimated that by mid-century over one billion people will be living in low-lying coastal zones and potentially impacted by rising oceans and storm surges.

The loss of ice sheets and glaciers is one of the more public faces of global warming. It is an image which the public is familiar with. There is a high, or a very high, level of confidence that these changes are widespread and increasing. Many populations depend on runoff from glaciers as a source of freshwater. As glacial supply of freshwater decreases, these populations will be at a significant risk of water insecurity.

Permafrost temperatures have increased to record high levels. In addition to the ecosystem changes that this will produce, the loss of permafrost opens up the possibility of very large releases of methane and other greenhouse gases that are sequestered in higher latitudes.

The IPCC has also concluded that it is virtually certain that the ocean has warmed. Up to this point, the oceans have absorbed more than 90% of the excess heat in the climate system. That has been at the cost of increased acidification and the decrease in oxygen content. Both of these have significant implications for marine biology and for food production. The IPCC can say with medium confidence that this is already affecting the maximum catch potential. This has significant implications for nutrition especially in the tropics for which the effects may be most marked.

Sea level changes are already occurring. Global mean sea level increased by 20 cm between 1901 and 2018. This is due in part to thermal expansion of the oceans as water absorbs heat and also due to melting of polar and Greenland ice sheets. Given that nearly 1,000,000 people will be living close to the ocean edge by mid-century, this is clearly a major concern. Small island nations of the Pacific are already under threat from a combination of rising sea levels and increased severity of storms. It can be anticipated that population displacement of millions of people will occur as a result of rising sea levels.

12 Regional Differences

The IPCC has published global maps of the change in temperature and precipitation by region. The IPCC AR6 Working Group 1 has developed an interactive atlas to allow the visualization of change by region (https://interactive-atlas.ipcc.ch).

Regarding temperature, as GMST reaches 1.5 °C, changes are seen in all land areas. Temperature rise will be most marked in the northern latitudes and least over southern South America. The Arctic and sub-Arctic areas are most impacted. Initially, the oceans are less affected due to their ability to buffer temperature rise. As the temperature reaches a mean global change of 2.0 °C, the changes in the Polar Regions are even more marked and all land areas are affected. The capacity of the oceans to buffer for the change in temperature is also being tested, and significant temperature rises will be seen in global surface water temperature.

This change in temperature affects the amount of water in the atmosphere and the wind patterns, which can carry water over the surface of the earth. At 1.5 °C of warming, a band of decreased precipitation will extend across the southwest United States, Central America, and northern South America. This will extend through the Mediterranean Basin to Western Asia. In the southern hemisphere, a band of decreased precipitation will affect the southwest coast of South America and the Northeast, and this band extends onto the continent of Africa affecting southern Africa and then onto southwestern Western Australia. These changes will be even more marked at 2 °C. These changes in temperature and precipitation will have profound implications for access to water and nutrition and for the security of billions of people.

12.1 Africa

Assessment Report 5 (AR5) of the IPCC reported on projections for Africa (AR5, 3: Africa) (Niang et al. 2014). Within Africa, there are marked differences in the projections for regions as the atmosphere warms. In general, all areas of Africa will be affected by temperature rise. It is highly likely that the mean surface temperature will increase by 2 °C by the end of the twenty-first century.

The precipitation patterns in Africa will vary. Southern Africa and northwest Africa will experience a decrease in precipitation. Some areas of Africa however can expect an increase in precipitation, especially in the central and eastern zones, but there is uncertainty about this. Overall, it is expected that water insecurity will increase.

The report concluded that there is already evidence of shifting ecosystems and species due to climate change. This will have important implications with regard to the factors associated with disease transmission.

Populations are already on the move globally with a shift from rural to urban areas. This trend may increase as migration between countries and between continents. Decreasing crop yields and competition for insecure water resources may lead to further migration and raise the likelihood of conflict between countries.

13 Adaptation

Even if greenhouse gas emissions into the atmosphere were to decrease immediately, the effect of gases already in the atmosphere will continue to warm the climate for decades and centuries to come. It is important that communities begin to adapt to the new reality of increased temperature. Adaptation can be defined as actions that reduce the effect of climate change (Natural Resources Canada n.d.).

Vulnerability is the extent to which the original population is susceptible to climate effects. The patterns of climate change vary markedly as does the ability of a population to withstand the changes. Some areas of the world will be affected less and may have sufficient resources to be able to adapt to the change and repair damage, a marker of resilience. Others, however, particularly lower-income economies, may be subject to extreme climate changes and may not have the economic, social, and political structures to adapt and respond. IPCC AR6 indicated that up to 3.6 billion people are in a highly vulnerable situation (IPCC 2022: AR6. SPM WGII B2). Climate-related disruption is already being seen even at the temperature rise of just over 1 °C. That will become much more pronounced in the coming decades as the temperature rises toward 2 °C.

There is evidence that adaptation measures are underway globally. These vary depending on the economic resources of the region, the imminent nature of the threat and local response to climate change. At present, the approach is mostly reactive rather than proactive, but that may change as the crisis evolves. Adaptation measures can be applied to many systems including land and ocean ecosystems, urban and infrastructure, and energy systems and across sectors. For example, climate change is associated with an increased risk of high rainfall events. Cities at present do not have sanitary systems that will be able to process the volume of rainfall. This will result in contamination of water supply and sewage runoff. Adaptation can address this by building capacity in the system for events that were formerly rare and reduce the risk to vulnerable populations of enteric infections. Some adaptation measures will support mitigation. An example of this is restoring marshes and flood plains that can accommodate river overflow. These not only serve as a potential source of carbon sequestration but also will help adapt to changing patterns of rainfall.

14 Conclusion

The science underlying climate change was clarified in the nineteenth century. Once the link between rising carbon dioxide levels in the atmosphere and a warming atmosphere became known, it was not seen as a threat. By the late twentieth century, however, the negative consequences of global warming were beginning to be appreciated. More powerful computers permitted the development of projections regarding what might happen as the atmosphere warmed. In addition, populations began to experience more severe rainfall and storm events coincident with the never rising global mean surface temperature. In response to this, the United Nations and other groups began to move countries toward greenhouse gas reduction. At present, it is not clear whether that effort will be sufficient to keep global mean surface temperature below 2 °C by the end of the century. Given that reality, it is important that countries begin to adapt to the new climate realities and prepare for the changes that are coming. This is especially important in Africa where a significant vulnerable population will face increasing challenges of changes in temperature, precipitation, and access to water and nutrition.

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