7.2 What are the causes of global warming?

To understand the causes of climate change, we must first understand the factors affecting the Earth's temperature, then identify whether they are natural or human-caused.

There are three factors affecting the Earth's temperature, namely, the amount of solar radiation reaching the Earth, the Earth's albedo and the atmospheric concentration of greenhouse gases. This section explains the mechanisms behind these factors and how scientists draw the conclusion of man-made climate change.

1 Factors affecting the Earth's temperature

2 Is global warming natural or human-caused?

More Information

What is global warming? What is climate change?

"Global warming" and "climate change" are closely related, but the latter has a broader meaning than the former.

"Global warming" refers to the temperature increase of the entire Earth since the early 20th century due to burning fossil fuels since the Industrial Revolution. The World Meteorological Organization (WMO) states that the global mean temperature in 2024 was about 1.55 ° C above pre-industrial levels.

"Climate change" refers to a wide range of global phenomena resulting from burning fossil fuels which increases atmospheric concentration of greenhouse gases. These phenomena include "global warming", sea level rise, the mass loss of the Greenland and Antarctic ice sheets, shrinking Arctic sea ice, glaciers retreat, more frequent extreme weather events as well as changes in phenology.

1 Factors affecting the Earth's temperature

The Sun is the Earth's primary source of energy. Solar radiation reaches the Earth in the form of shortwave radiation (mainly visible light). After going through a series of physical processes including reflection, absorption, evaporation, conduction, convection and radiation, some of the energy is directly reflected back to space, some is distributed among different Earth systems, e.g. atmosphere, ocean, land and ice sheet, and some is radiated back into space in the form of longwave radiation. (Fig. 1)

If the energy reaching the Earth exceeds the energy leaving it, a positive energy imbalance occurs, leading to the warming of the Earth. If the energy reaching the Earth is less than the energy leaving it, a negative energy imbalance occurs, resulting in cooling of the Earth.

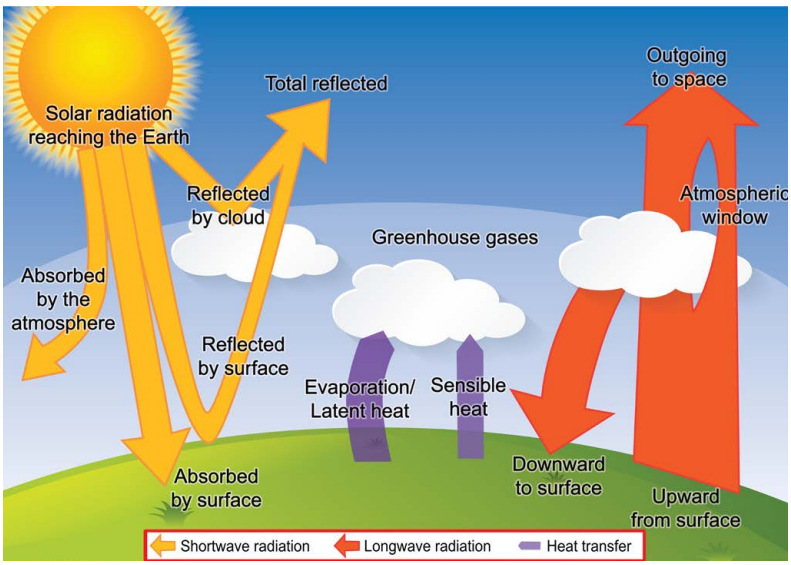


Fig 1

Earth's energy budget

There are three factors affecting the Earth's temperature, namely, the solar radiation reaching the Earth, the Earth's albedo and the atmospheric concentration of greenhouse gases.

Factors affecting the Earth's temperature		Questions	Interpretations
Solar radiation reaching the Earth	Solar activity	Has solar activity increased or decreased in recent years?	The intensity of solar activity affects the output of solar energy.
	Earth's orbit	How does Earth's orbit aound the Sun influence the solar radiation reaching the Earth?	The Earth's orbit around the Sun changes over time. These orbital variations affect the distance between the Earth and the Sun, altering the amount of solar radiation reaching the Earth.
Albedo	Surface cover	Why does it matter how much of the Earth is covered by sea ice and snow cover?	Sea ice and snow have high albedo. Hence the changes in ice and snow cover play an important role in regulating the Earth's climate.
	Suspended particulates in the atmosphere	Why may volcanic eruptions increase the Earth's albedo?	Strong volcanic eruptions may lead to the formation of aerosols in the troposphere that helps to reflect large amount of solar radiation back into space.
Atmospheric concentration of greenhouse gases	Natural carbon cycle	Why is carbon dioxide of an undisturbed natural carbon cycle vital for life on the Earth?	Greenhouse gases naturally occur in the atmosphere. The atmospheric carbon dioxide regulates Earth's temperature through the natural greenhouse effect that keeps the Earth warm, creating a climate suitable for many species to flourish.
	Human activities	What is the relationship between human activities and climate change?	Human activities release greenhouse gases into the atmosphere that enhanced the greenhouse effect, causing global warming.

1.1 Solar radiation

Solar radiation refers to the energy continuously emitted by the Sun in the form of electromagnetic waves, also known as solar energy. The electromagnetic waves emitted by the Sun cover a wide range of wavelengths, but the energy is mainly distributed in the ultraviolet, visible, and infrared parts of the spectrum. Most of the energy is concentrated in the visible light and infrared regions of the spectrum, with ultraviolet radiation accounting for only a very small portion.

More Information

Climate Change: Incoming Sunlight

1.1.1 Solar activity

Fluctuations in solar activity are natural. Satellite–based instruments have been measuring the amount of solar energy reaching the top of the atmosphere (also known as total solar irradiance, TSI) since the late 1970s. The average value of TSI has been found to be about 1,361 W/m^2.

Although solar activity follows a cycle of roughly 11 years, the average fluctuation of TSI over the past several solar cycles is only about 0.1%. For pre–satellite era, TSI variations had to be estimated from sunspot numbers or radioisotope analyses of polar ice and tree rings.

Fig. 2 shows that since the early 20th century, both total solar irradiance and the global average temperature have showed an increasing trend. However, since the mid–20th century, total solar irradiance has shown a decreasing trend, while the global average temperature has continued to rise.

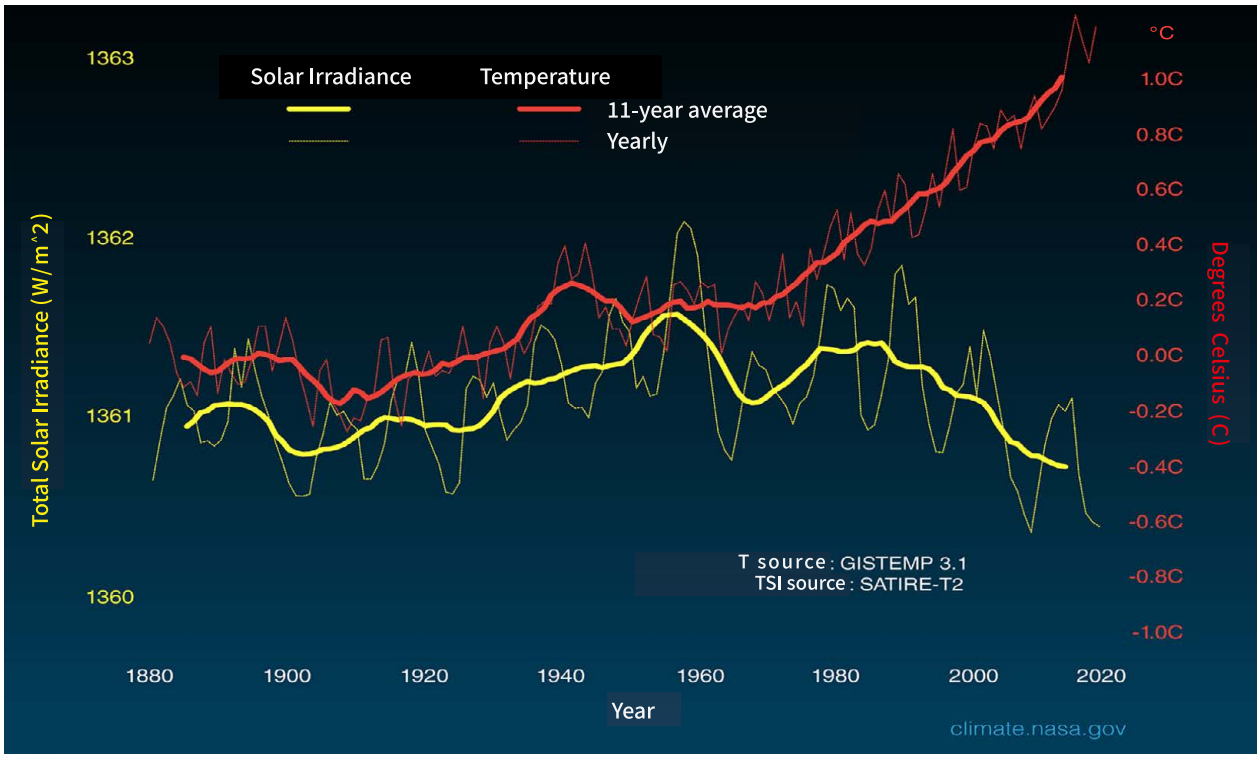


Fig 2 Total solar irradiance and global surface temperature changes
Source: National Aeronautics and Space Administration (NASA)

1.1.2 Earth's orbit (Milankovitch Cycles)

The Earth's orbit around the Sun changes throughout the time. There are also natural variations in the parameters of the Earth's rotation. In the early 20th century, Milutin Milankovitch, a Serbian astronomer, proposed that the advance and retreat of ice ages on Earth were closely related to three orbital geometric parameters of Earth's revolution around the Sun. The variations of these three parameters are referred to as Milankovitch Cycles. See Fig. 3 for further details.

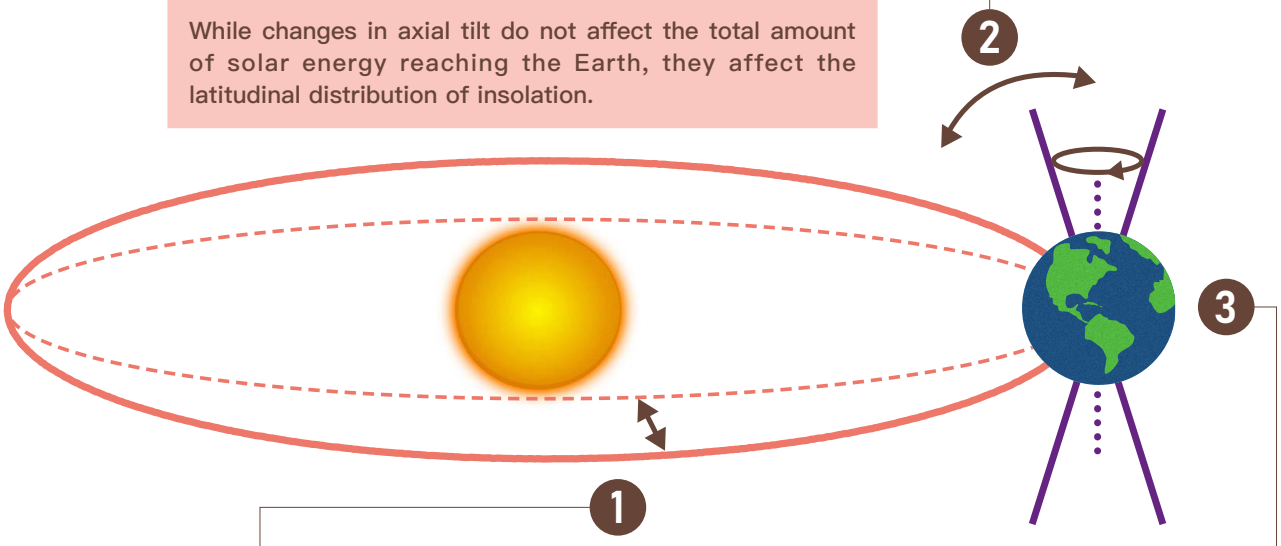
More Information

"Cool Met Stuff": Milankovitch Cycles

Parameter 2
Earth's axial tilt

The second parameter is the tilt of Earth's rotational axis. The axial tilt varies between 22.1° and 24.5 ° in a cycle of around 40,000 years.

While changes in axial tilt do not affect the total amount of solar energy reaching the Earth, they affect the latitudinal distribution of insolation.



Parameter 1
Shape of Earth's orbit around the Sun

The first parameter is the shape of Earth's orbit around the Sun. The orbit changes from nearly circular to elliptical in a periodical manner.

The full cycle takes about 100,000 years. These orbital changes influence the amount of solar energy reaching the Earth in different seasons.

Parameter 3
Precession of Earth's rotational axis

The third parameter is the precession of Earth's rotational axis, i.e. the wobbling of Earth's axis. A full cycle of the wobbling takes about 26,000 years.

Changes in this parameter also affect the latitudinal distribution of insolation. However, they do not affect the total amount of solar energy reaching the Earth.

Fig 3 Milankovitch Cycles

1.1.3 Are Milankovitch Cycles responsible for recent climate change?

Milankovitch Cycles are natural variations that occur over timescales of tens of thousands of years. It is difficult to explain the Earth's abrupt warming observed over the past hundred years by Milankovitch Cycles.

According to the Milankovitch Cycles, the Earth should currently be in a cooling phase. This prediction aligns with paleoclimate studies, which reveal that the Earth had been cooling slowly for about five thousand years before the Industrial Revolution. However, this slow cooling trend spanning the past five thousand years was completely reversed by the abrupt warming in the recent century.

More Information

Will the Earth return to ice age again?

1.2 Albedo

1.2.1 Surface cover

Light–coloured surfaces (such as desert, ice and snow cover) have higher albedo than dark–coloured ones (such as forest). At the same time, oceans absorb and store a greater amount of solar radiation than land due to different physical properties. At polar areas, it is found that sea ice reflects about 50–70% of solar radiation, showing a much higher albedo than polar seas. Snow has an even higher albedo than sea ice, reflecting around 90% of the incoming solar radiation. (Fig. 4)

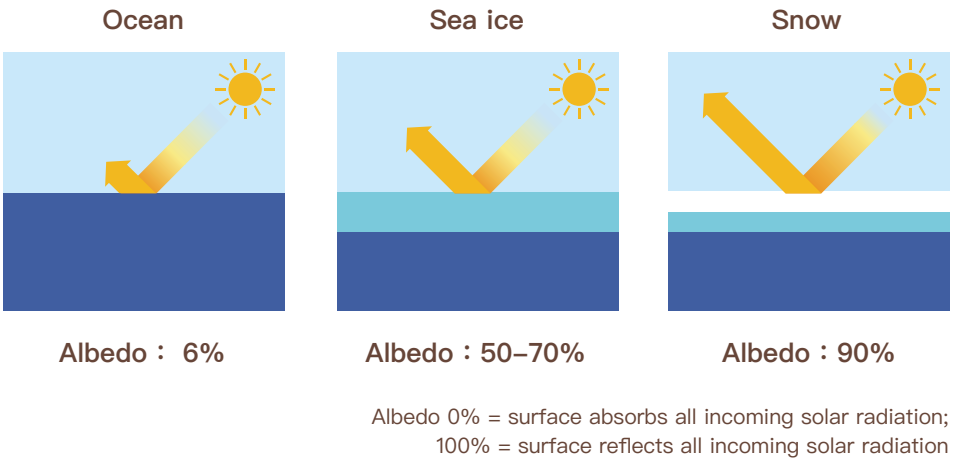


Fig 4 Albedo of different surfaces
Data Source: National Snow and Ice Data Center (NSIDC)

1.2.2 Volcanic eruptions

Volcanic eruptions are natural phenomena which release large amounts of gases, volcanic ash and particulates into the atmosphere. In small-scale eruptions, these gases and particulates are usually well contained in the troposphere, and will likely be washed out by rain within a couple of weeks. Powerful eruptions are capable of blasting large amout of sulfur dioxide (SO_2) into the stratosphere, where it reacts with water vapour to form sulfate aerosols and can remain stable for several years. These tiny sulfate particles are highly effective at reflecting solar radiation back into space, reducing the amount of solar radiation that reaches and heats the Earth's surface. These additional aerosols increase the Earth's albedo and cause a short-term cooling effect.

More Information

Ultimate Volcanic Expedition: The Cause of Global Warming?

The 1991 eruption of Mount Pinatubo in the Philippines is one of the examples of major volcanic eruptions leading to a drop in global average temperature. The eruption lowered the global average temperature by about 0.5 ° C in the following 18 months. However, the temperature returned to the pre-eruption level a few years later. (Fig. 5a, 5b)

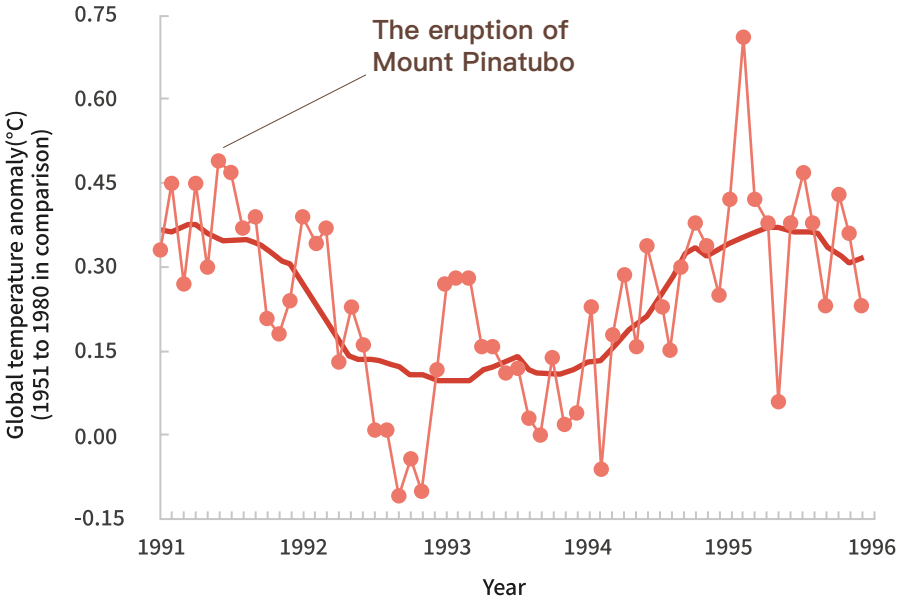


Fig 5a Global average temperature variation (1991 – 1996)
Source: HKO

Fig 5b
The eruption of Mount Pinatubo in the Philippines
Source: U. S. Geological Survey Photograph taken by Richard P. Hoblitt

Do volcanoes emit more carbon dioxide than human activities?

One of the natural factors affecting the climate is volcanic eruptions, in which carbon dioxide is released to the atmosphere. However, as indicated by various studies, over the past century, the annual amount of carbon dioxide emitted by human activities has far exceeded the total emissions from both terrestrial and submarine volcanoes. Data shows that human activities emit at least 60 times more carbon dioxide than volcanoes each year.

More Information

1.2.3 "Climate – Albedo" feedback

"Climate–albedo" feedback is a process where the change in Earth's albedo caused by climate change will amplify climate change. This process creates a positive feedback loop where warming (or cooling) of the planet will promote further warming (or cooling), creating a vicious cycle.

According to Milankovitch, the impact of the three orbital geometric parameters of Earth's revolution around the Sun on the amount of insolation reaching the high latitudes in the Northern Hemisphere, where most of the ice and snow on Earth are found, is particularly important. Variation in ice and snow cover can lead to a positive feedback mechanism.

For example, when the amount of insolation reaching the northern high latitudes decreases, summer heat is not sufficient to melt all the ice and snow precipitated in the preceding winter, leading to an overall increase of ice and snow in the course of the year. Increasing ice and snow will reflect more sunlight back into space, thereby reducing the amount of heat absorbed on Earth. This will set up a vicious cycle that supports further growth of ice and snow. Persistent increase in ice and snow year after year will eventually push the Earth into an ice age.

More Information

According to studies from 2023 and 2024, the Arctic was warming at a rate approximately three times faster than the global average. Positive "climate — albedo" feedback was a major cause of this phenomenon.

Global warming has led to the melting of ice and snow in the Arctic, exposing the darker and less reflective surfaces of land and ocean. The Arctic thus absorbs more solar energy, enhancing warming and accelerating the melting of ice and snow in a vicious cycle.

1.3 Greenhouse gases

More Information

Cool Met Stuff: Greenhouse Effect

Greenhouse effect and global warming

What is carbon cycle?

The global climate has always been affected by factors such as solar activity, changes in the Earth's orbit, and volcanic activities. However, the continuous increase in greenhouse gas concentrations in the atmosphere has completely surpassed the effects of these natural factors since the Industrial Revolution. Climate change caused by human activities has now become one of the greatest challenges facing humanity.

1.3.1 Types of greenhouse gases

The main greenhouse gases in the atmosphere include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Data shows that the atmospheric concentrations of these greenhouse gases steadily increase. Although water vapour (H_2O) is the primary contributor to the natural greenhouse effect, it is generally believed that its concentration in the atmosphere is not directly affected by human activities.

1.3.2 Greenhouse effect

Greenhouse effect is a term that refers to a physical property of the Earth's atmosphere. If the Earth had no atmosphere, its average surface temperature would be about –18° C, a very low temperature, rather than the comfortable 15° C found today. The difference in temperature is due to a suite of gases called greenhouse gases in the atmosphere.

When solar radiation reaches the Earth, the atmosphere and Earth's surface reflect part of the insolation back into space, which is known as the Earth albedo. At the same time, Earth's surface absorbs part of the insolation, warms, and then emits infrared radiation. A small part of this infrared radiation escapes into space through the atmosphere, while most of it is absorbed and scattered in all directions by atmospheric greenhouse gases. This is how the atmosphere is warmed from below. These gases will eventually re-radiate infrared radiation back to the Earth's surface, keeping the Earth's surface and the lower part of the atmosphere warm. This process is called the natural greenhouse effect. (Fig. 6) Therefore, the concentration of greenhouse gases in the atmosphere directly influences the Earth's overall energy balance.

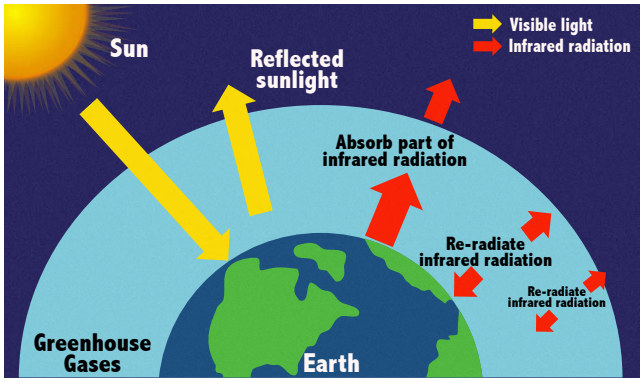


Fig 6
Greenhouse effect
Source: HKO

1.3.3 Carbon cycle

The carbon cycle is a biogeochemical cycle in which carbon is continuously exchanged and recycled among several natural reservoirs, including the atmosphere, oceans, biosphere, rocks and fossil fuels, where carbon is stored.

In an undisturbed natural carbon cycle, these exchanges between reservoirs are approximately balanced.

In the last 800,000 years before the Industrial Revolution, the atmospheric concentration of carbon dioxide fluctuated roughly between 180 and 280 ppm. However, human activities have disrupted the global carbon cycle. In 2023, the atmospheric concentration of carbon dioxide has reached 420 ppm, the highest level in the past 2 million years. (Fig.7)

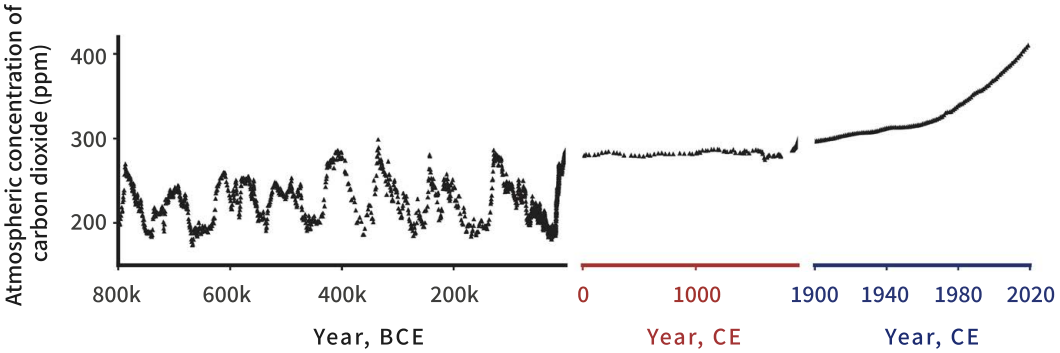


Fig 7 The atmospheric concentration of carbon dioxide
Source: IPCC Sixth Assessment Report

1.3.4 What human activities increase greenhouse gases?

Human activities emit large amount of greenhouse gases to the atmosphere, enhancing the greenhouse effect by trapping more heat energy on Earth and leading to global warming.

Human activities	Human activities	Human activities
Burning fossil fuels Deforestation Use of machines Cement production Waste incineration	Extracting fossil fuels Pastoral farming Paddy farming Waste decomposition	Burning fossil fuels Deforestation Use of machines Cement production Waste incineration
Carbon dioxide CO_2	Methane CH_4	Nitrous oxide N_2O

1.3.4.1 Burning fossil fuels

Fossil fuels include coal, oil and natural gas. Humans have extracted and burned massive amounts of fossil fuels for many purposes since the Industrial Revolution, such as power generation, heating and powering machines and vehicles. Large amounts of carbon dioxide, methane and nitrous oxide are emitted to the atmosphere.

1.3.4.2 Deforestation

To acquire land for agricultural and urban development, forests are cut down and then burned on a massive scale. Carbon dioxide is released from the biomass through the burning process. Moreover, plants capable of absorbing and storing carbon dioxide decrease, resulting in increasing atmospheric concentration of carbon dioxide. Data shows that around 178 million hectares of forest were lost globally for 1990–2020.

More Information

Latest atmospheric level of carbon dioxide

Historical trends in atmospheric carbon dioxide

1.3.4.3 Agricultural activities

Pastoral farming emits a lot of methane through cows ruminating, as does paddy farming. The use of large amounts of nitrogen fertilizers releases nitrous oxide. Moreover, agricultural machines are mostly powered by fossil fuels, contributing to carbon dioxide emission.

1.3.4.4 Industrial activities

Industrial activities emit large amounts of anthropogenic greenhouse gases. For example, nylon production releases nitrous oxide and the production of cement releases carbon dioxide. Chlorofluorocarbons (CFCs), which were developed and used as refrigerants and aerosol propellants in the past century, are synthetic gases, intensifying greenhouse effect.

1.3.4.5 Waste treatment

With improving living standard and the rise of consumerism, humans consume resources and produce large amount of waste as well. Waste is mainly treated by incineration or landfilling. The incineration process produces carbon dioxide, methane and nitrous oxide, while waste decomposition in landfills produces methane..

In 2023, the atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased by 51%, 165% and 25% respectively compared to pre-industrial levels. (Fig. 8)

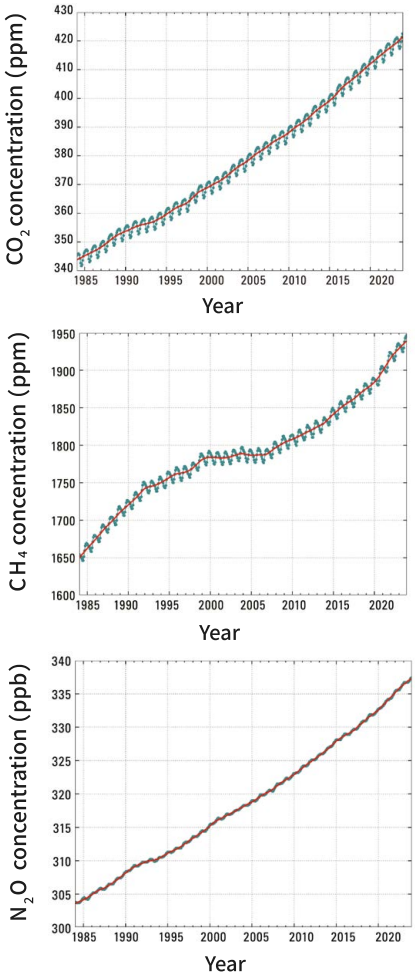


Fig 8

Trends in atmospheric concentrations of carbon dioxide, methane and nitrous oxide
Source: WMO Greenhouse Gas Bulletin

Temperature variations in troposphere and stratosphere

If solar activity were the main cause of global warming, the temperature of the whole atmosphere would be affected. If global warming is mainly caused by greenhouse gases, the increase in greenhouse gases will increase the temperature in the troposphere while the stratosphere will cool. This is a distinctive characteristic of an intensifying greenhouse effect. Data shows a rising temperature in troposphere while the stratospheric temperature has been declining since the mid-20th century.

More Information

Simulation of atmospheric carbon dioxide

WMO Greenhouse Gas Bulletin

Latest atmospheric level of methane

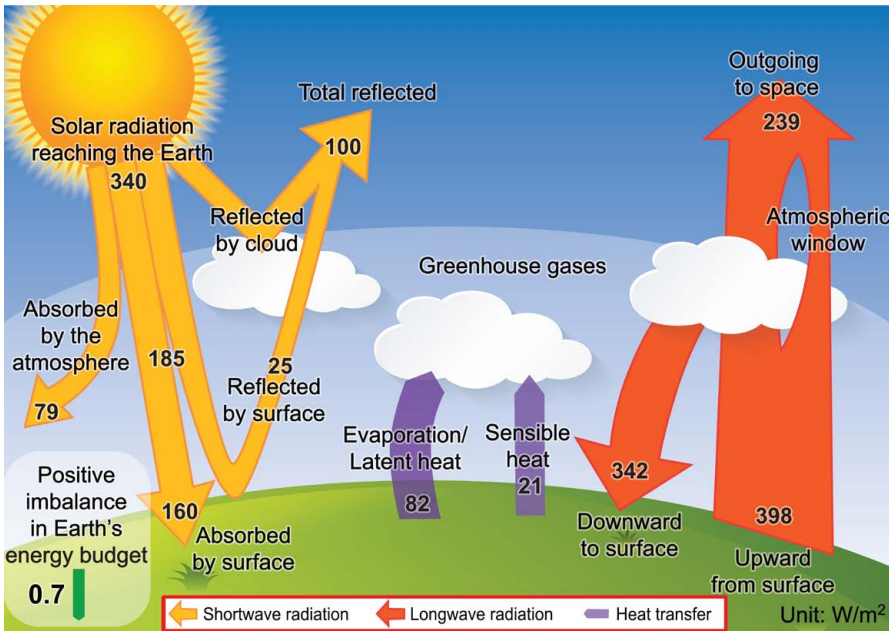
Latest atmospheric level of nitrous oxide

More Information

IPCC Sixth Assessment Report Working Group 1, chapter 2.3.1.2.2

Couldn't the Sun be the cause of global warming?

2 Is global warming natural or human-caused?



More Information

The causes of climate change

Fig 9

Present–day Earth's energy budget
Source: IPCC Sixth Assessment Report

Scientists synthesized relevant data from multiple studies, and the results indicate that the Earth's current energy budget has an approximate positive imbalance of 0.7 W/m2, leading to global warming. (Fig.9)

Why is there an imbalance in the Earth's energy budget? Scientists use computer climate models to simulate the change in global surface temperature over the past 170 years. Fig. 10 shows the simulation results of temperature anomalies under different scenarios. The results align with the observed changes in Earth temperature when both natural factors (solar activities and volcanic eruptions) and human factors (including changes in atmospheric greenhouse gas concentrations and land use, as well as man–made pollution) are considered. Hence, the Sixth Assessment Report of IPCC clearly points out that it is unequivocal that human influence has warmed the atmosphere, ocean and land.

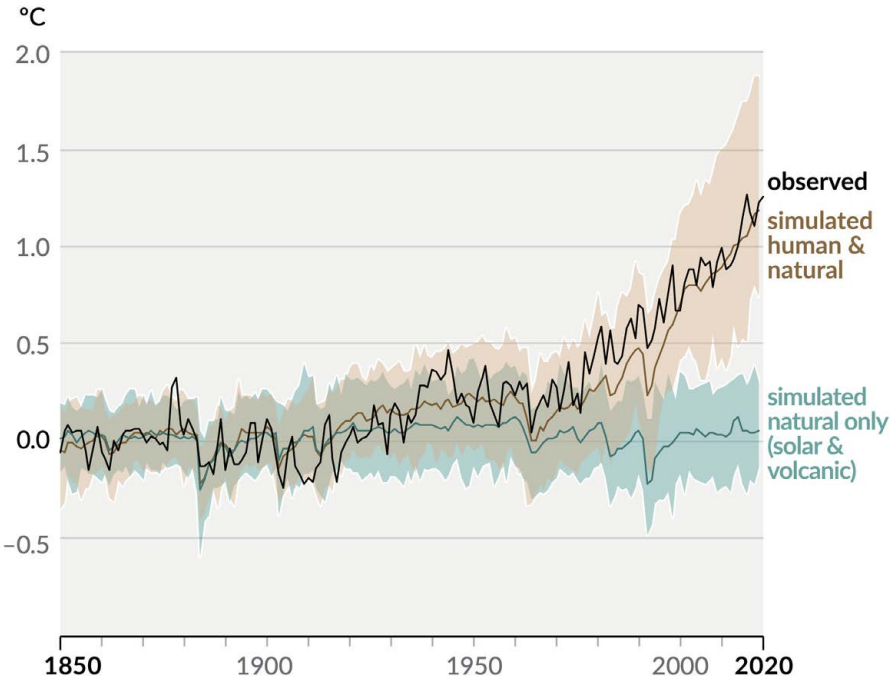


Fig 10

Changes in global surface temperature relative to 1850–1900
Source: IPCC Sixth Assessment Report

2.1 Human-driven factors

More Information

The 97% consensus on global warming

The Sixth Assessment Report of the IPCC summarizes both natural and human factors contributing to global warming. Fig. 11 (a) shows that between 2010 and 2019, the Earth's surface temperature increased by more than 1 ° C compared to the baseline period of 1850—1900. Fig. 11 (b) presents attribution research assessing the contributions to global warming, which indicates that human activities are the largest contributor, while natural factors, (such as internal climate variability, solar and volcanic activities) have have relatively insignificant contributions. Fig. 11 (c) illustrates findings from radiative forcing studies, which assess the contributions of different factors to global warming. These studies show that various components of human activities (including greenhouse gases, aerosols and their precursors, land use changes, and aviation contrails) have affected global warming, with carbon dioxide and methane being the most significant contributors.

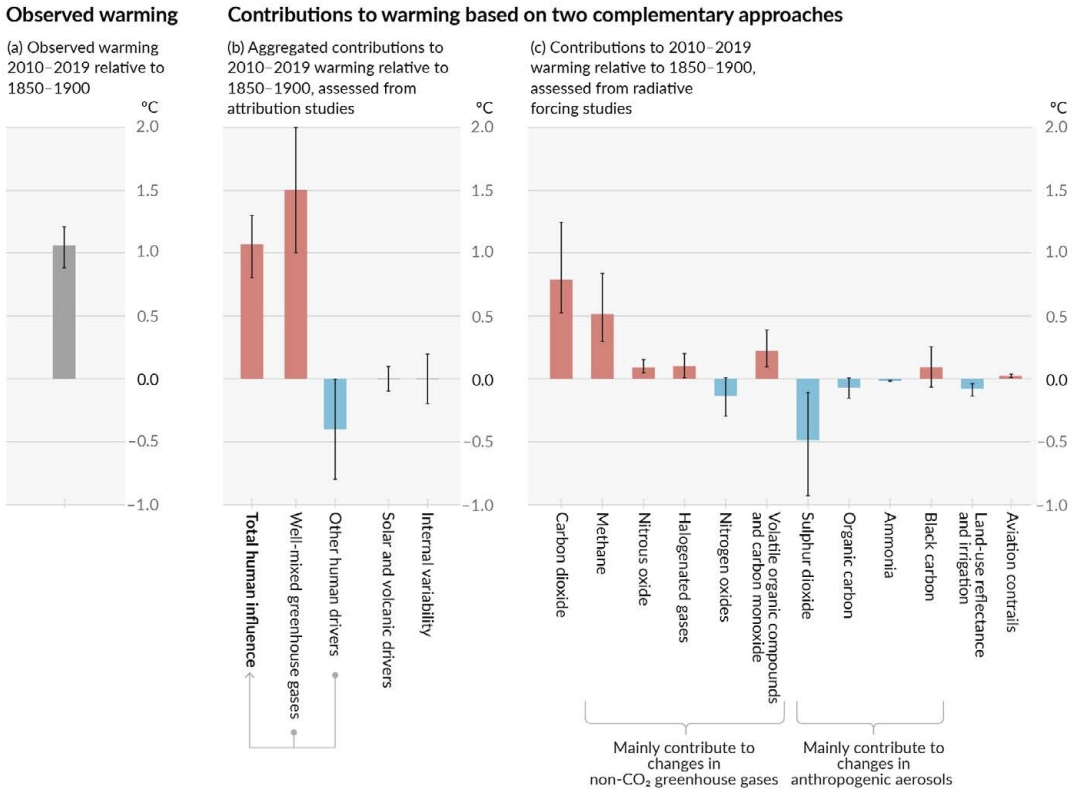


Fig 11 Assessed contributions to observed warming in 2010–2019 relative to 1850–1900
Source: IPCC Sixth Assessment Report

2.2 Scientific consensus

Over the past 30 years, many studies have examined the consensus on human–caused global warming among climate scientists. The scientific consensus has exceeded 90%. Lynas et al. (2021) randomly selected climate–related peer–reviewed papers published since 2012 for analysis. The study found that the scientific consensus on human–caused climate change exceeds 99%. (Fig.12)

Fig 12 Scientific consensus on human–caused global warming among climate scientists
Source:Skeptical Science

Assessment Reports of Intergovernmental Panel on Climate Change (IPCC)

IPCC publishes assessment reports every several years, summarizing the results of scientific research worldwide. The assessment reports represent the scientific consensus on climate change. The IPCC has published six assessment reports since 1990. The main conclusions of each report are as follows.

1990
The First Assessment Report

- Global mean surface temperature has increased by 0.3˚C to 0.6˚C over the last 100 years
- The magnitude of this warming is broadly consistent with climate model predictions, but it is also similar in scale to natural climate variability

1995
The Second Assessment Report

- The balance of evidence suggests that there is a discernible human influence on global climate

2001
The Third Assessment Report

- The warming over the past 100 years is very unlikely (1–10% chance) to be due to internal variability alone
- Most of the observed warming over the last 50 years is likely to have been caused by increased greenhouse gas concentrations

2007
The Fourth Assessment Report

- Warming of the climate system is unequivocal
- Most of the observed increase in global average temperature since the mid–20th century is very likely (>90% chance) due to the observed increase in human–caused greenhouse gas concentrations

2013
The Fifth Assessment Report

- Warming of the climate system is unequivocal. Since the 1950s, many observed changes are unprecedented over decades to millennia
- It is extremely likely (95–100% chance) that human influence has been the dominant cause of the observed warming since the mid–20th century

2021
The Sixth Assessment Report

- It is unequivocal that human influence has warmed the atmosphere, ocean and land. The rate of global warming is the fastest in at least the past 2,000 years. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred
- Human–induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since the Fifth Assessment Report

More Information

Global warming:
An imminent crisis

7.2 Chapter Summary

What are the causes of global warming?

1 Climate and weather

Solar radiation

- The Sun is the Earth's primary source of energy. If the energy reaching the Earth exceeds the energy leaving it, the Earth warms.
- Changes in the Earth's orbit affect the amount of solar radiation reaching the Earth, but they occur over timescales of tens of thousands of years. These changes cannot explain the abrupt warming observed over the past hundred years.

Albedo

- Surface cover, such as oceans and sea ice affects the reflection of solar radiation. Climate change leads to the melting of ice and snow, which lowers albedo and accelerates climate change, creating a vicious cycle.
- Volcanic eruptions increase the amounts of atmospheric aerosols, reflecting more solar radiation back into space and reducing the amount of heat absorbed by the Earth.

Greenhouse gases

- Greenhouse gases such as carbon dioxide, methane, and nitrous oxide naturally occur in the atmosphere. The natural greenhouse effect keeps the Earth at a habitable temperature.
- Human activities, such as burning fossil fuels, deforestation, agricultural activities and industrial activities, intensify the greenhouse effect, leading to global warming.

2 Global warming is caused by human activities

- Natural factors cannot fully explain the abrupt rise in global temperature. Both research studies and simulations indicate that human activities are the primary cause of global warming.
- Over 90% of climate scientists agree that human activities cause global warming, showing a strong scientific consensus.