

Chapter 5

Climate Change Trends

Abstract Global warming started when humans began altering the chemistry of the atmosphere by agricultural practices about 10,000 years ago and was exacerbated by the beginning of the Industrial Revolution due to the increased burning of coal as a cheap source of energy. As a result of these factors, and the mass production of the internal combustion engine, greenhouse gases have been building up in the atmosphere for the past 10,000 years. There are certain observable trends that are and have been taking place, especially during the latter half of the twentieth century and into the twenty-first. Among these are rising temperatures over land and sea, receding glaciers and rising sea level. Other climate change trends are listed and further discussed in this chapter. Different temperature scales used in climate science are Celsius, Fahrenheit, and Kelvin. The features of temperature graphs are explained and examples given. A typical meteorological station is described and illustrated. Sources of temperature data are discussed as well as potential problems with the data. The BEST study, their reasons, and their results are explained as are methane clathrates and climate change perturbations and attribution.

Keywords Celsius • El Niño • Centigrade • Pyranometer • GISS • ENSO • BEST • NCDC • Climate change • Trends • Kelvin • Fahrenheit • Absolute zero • UAH • RSS • Extinctions • Tropospheric warming • Stratospheric cooling • Perturbations • NOAA • Rocketsondes • Arctic ice • Proxies • Arctic warming • SSTs • Permafrost • Meteorological station • Methane • Clathrates • Radiosondes • Attribution • Forcings • Feedbacks • Temperature

Things to Know

The following is a list of things to know from this chapter. It is intended, as it is in each chapter, to serve as a guide to points of emphasis for the student to keep in mind while reading the chapter. Before finishing with this and every chapter, the “Things to Know” should be understood and can be used for review purposes. The list may not include all of the terms and concepts required by the instructor for this topic.

Things to Know	
Climate Change Trends	Temperature Scales
Attribution	BEST
Forcings	Tropospheric warming
El Niño	NCDC
Feedbacks	Kelvin
Arctic Ice	Climate perturbations
Absolute zero	Stratospheric cooling
Sea-surface temperatures	NOAA
Radiosondes	Animal and plant extinctions
Methane Clathrates	RSS
Land-based meteorological station	Permafrost
Proxy	Pyranometer

5.1 Climate Change Trends

How do we know the climate is changing and the Earth is warming? The list of reasons given below shows some of the main reasons that we know but there are others that will be discussed later in this text. The most obvious indicators that the Earth is warming are the following:

1. Increased humidity in the atmosphere;
2. Increased evaporation of ocean and fresh water and moisture from soils;
3. Increasing frequency and intensity of storms and unusual weather patterns;
4. Melting glaciers;
5. Melting permafrost and release of methane to the atmosphere;
6. Decreasing snow cover in winter;
7. Temperature increases over land and sea;
8. Temperature increases in boreholes;
9. Increase in ocean heat content;
10. Increasing air temperatures in the lower atmosphere (troposphere);
11. Increasing temperature of the upper crust of the solid Earth;
12. Cooling of the stratosphere;
13. Plants and animals shifting to higher latitudes and altitudes;
14. Sea level rising;
15. Ice sheets, glaciers, and sea ice melting;

16. Spring coming earlier and fall later in the year;
17. Ocean acidification; ocean waters are becoming more acidic;
18. Nights warming more rapidly than days;
19. Outbreaks of pest infestations earlier each year;
20. Increase of animal and plant species extinction.

5.2 Rising Temperatures

Are temperatures rising all over the Earth? And if so, how do we know? How fast are temperatures rising, if they are rising, and why?

Temperature records tell us that some places on Earth are getting warmer while others are getting colder depending on the season of the year and local factors. But how do we know that the Earth as a whole is growing warmer, cooler, or staying the same? How do we arrive at a global average temperature for the Earth? If we could calculate an annual global temperature for a series of years we could see if the Earth is warming, cooling, or staying the same over a certain period of time, and this has been done by scientists at NASA's Goddard Institute of Space Studies (GISS) as well as by others.

To obtain the annual average temperature for the Earth, it seems that all scientists would need to do is add all of the temperature readings from the Earth and divide by the number of readings. That procedure would give scientists a number but it would not be an accurate or meaningful number. Some of the reasons why that number would not be accurate are as follows:

- Most of the readings would be from the Northern Hemisphere because most of the land and the people with thermometers are in the Northern Hemisphere, so the average would not be a world-wide average;
- Some of the readings would be from different seasons of the year and one season may be represented by more readings than another season;
- Some of the readings would be from nighttime, others from daytime and there could be more of one than the other;
- Some readings would be from old weather stations located near vents or surrounded by asphalt or city buildings (the heat-island effect) and this would increase the average temperature;
- Temperature readings from one station may be reporting more temperature readings than other stations.

Fortunately, a method for calculating the Earth's global average temperature was devised by scientists at NASA's Goddard Institute of Space Studies (GISS) in the 1970s which will be described later in this text after we first look at different ways to measure temperature; and the different temperature scales that are used internationally to record and refer to temperatures.

A recent (2011) paper published in *Environmental Research Letters* extracted the human-caused global warming signal from the global surface temperature and lower atmosphere (troposphere) temperature data. In order to accomplish this, the authors

filtered out the effects of solar activity, the El Niño Southern Oscillation (ENSO), and the volcanic activity from the data. The result of this study confirmed the warming trend presented by earlier workers.

5.2.1 *Temperature Scales*

To be able to measure and to report temperature readings in a meaningful way, universal temperature scales have been devised. The most commonly used scales are Fahrenheit (°F) and Celsius (°C) but there are other temperature scales used for different purposes. The Kelvin (K) scale is also used in climate science but Celsius (the same as Centigrade) is used most often as can be seen in the majority of the graphs present in this text. The following illustrations (Fig. 5.1 and Table 5.1) compare the three most commonly used temperature scales used in climate change science.

Some baseline temperatures in the three most commonly used temperature scales are shown below in Fig. 5.1.

The following equations allow conversion between the Celsius and Fahrenheit temperature scales:

$$\text{Temperature Celsius } (T_c) = 0.55 (T_f - 32)$$

$$\text{Temperature Fahrenheit } (T_f) = 1.8T_c + 32$$

A Celsius to Fahrenheit and *vice versa* conversion program can be found at the following web site: <http://www.wbuf.noaa.gov/tempfc.htm>. By entering the temperature in either Celsius or Fahrenheit, the equivalent temperature in the other scale is automatically shown.

The Kelvin scale has no degrees but is simply divided into units Kelvin (1 unit K equals 1 degree Celsius or Centigrade). The lowest point on the Kelvin scale is absolute zero, the point at which matter becomes stationary (subatomic particles become frozen). Absolute zero Kelvin is equivalent to -273°C . Thus, 0°C is 273 K. Each degree on the Celsius scale is +273 K. Thus, 10°C is 283 K. The Kelvin scale is stated without degrees and is reported with just a number. There are no minus numbers to the Kelvin scale and nothing has ever been reduced in temperature to zero K.

5.2.2 *Temperatures Shown by Graphs*

Temperatures shown by plotting annual global temperatures against time are shown in the illustration Fig. 1.1 in the Introduction. It is possible in this way to show temperature trends through time and visually determine that the Earth is warming, cooling, or staying about the same.

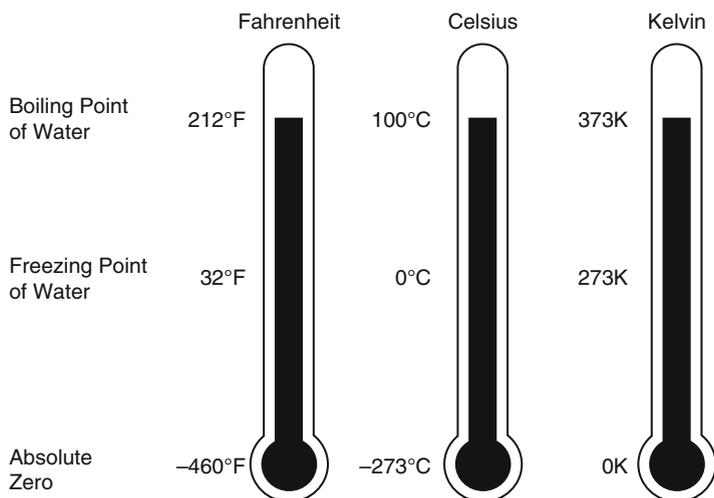


Fig. 5.1 Celsius, Fahrenheit, and Kelvin temperature scales. The Celsius scale is also called the centigrade temperature scale, and is the scale based on 0 for the freezing point of water and 100 for the boiling point of water. Invented in 1742 by the Swedish astronomer Anders Celsius, it is sometimes called the centigrade scale because of the 100-degree interval between the defined points. The following formula can be used to convert a temperature from its representation on the Fahrenheit (F) scale to the Celsius (C) value: $C = 5/9(F - 32)$. The Celsius scale is in general use wherever metric units have become accepted, and it is used in scientific work everywhere (Redrawn from website cfbt-us.com with permission from Ed Hartin)

Table 5.1 Scales commonly used when discussing temperature, Fahrenheit, Kelvin, and Celsius

Commonly used temperature scales			
Temperature	Kelvin	Degree Celsius	Degree Fahrenheit
Symbol	K	°C	°F
Boiling point of water	373.15	100	212
Melting point of ice	273.15	0	32
Absolute zero	0.	-273.15	-459.67

Temperatures in the graphs shown in this text are given in degrees Celsius (°C) unless otherwise stated. They are also given as temperature anomalies which are temperatures as compared to an average global temperature for a stated interval of time (as the global average for the temperatures during the period 1951–1980 in Fig. 1.1). By using this method of referring to temperature it can be easily seen that Earth’s temperature is warming, cooling, or staying the same for a given unit of time.

Let’s look at what can be gleaned from Fig. 1.1. There are two axes to the graph: the x-axis along the bottom giving the number of years from 1880 to 2000 and beyond. The vertical or y-axis is stated as the temperature anomaly and given in °C. The 0° position on the y-axis represents the average temperature for the period

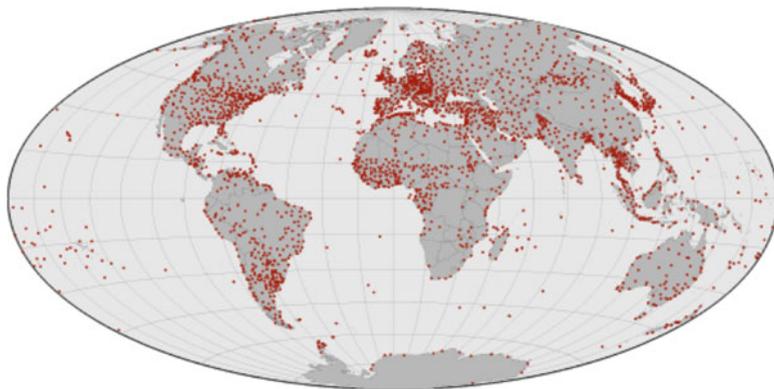


Fig. 5.2 Weather stations (*red dots*) are scattered unevenly across the globe. They are especially sparse in Africa and over the oceans. Before scientists could be confident in global temperature records, they needed to demonstrate that widely spaced observations captured global temperature trends accurately (NASA map by Robert Simmon, based on data from the National Climatic Data Center, Public Domain)

1951–1980, as stated in the caption, and all temperatures on the graph are plotted with reference to the 0° point, either positive (above) or negative (below) 0° .

There is a series of black squares along the x-axis connected by a thin black line and identified in the graph as the annual mean. There is a red line bisecting the black line identified as the 5-year running mean and as expected the two lines are roughly parallel. As can be seen in the graph (Fig. 1.1), there was a slight cooling beginning around 1880 until 1890, then a slight warming followed by a cooling until around 1910, then a gradual and pretty consistent warming until about 1940, then a slight cooling through the 1970s, and then an almost constant warming until the present time (beyond 2000; the last number on the x-axis).

The black squares in Fig. 1.1 are annual means and the red line is a 5-year running mean. Note the green vertical bars which represent uncertainty; their length indicates the degree of uncertainty. The green bars become shorter as the temperature plot approaches the present reflecting greater confidence in temperature measurements as instrumentation and quality control improve.

The method of calculating a global average temperature was originally devised with the understanding that the sample of temperature readings was heavily biased toward the Northern Hemisphere.

Absolute estimates of global average surface temperature are difficult to compile for several reasons. Some regions have few temperature measurement stations, such as the Sahara Desert and Antarctica, and interpolation must be made over large, data-sparse regions. The distribution of weather stations over the Earth's surface is represented by the illustration above (Fig. 5.2).

By stating the temperatures as anomalies and as a temperature index, confusion with raw temperature data is avoided. Skeptics disagree with the method of average temperature methodology. Often the disagreement is due to simple denial of the warming

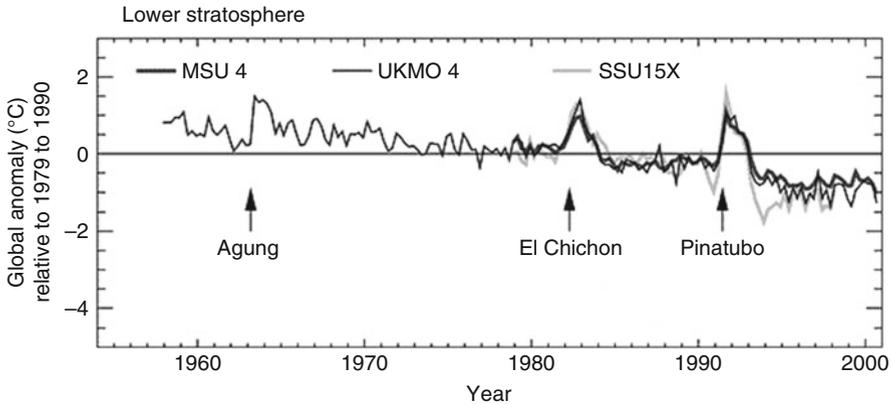


Fig. 5.3 Microwave sounding unit (MSU) lower troposphere and lower stratosphere 1979–2010 temperature trend ($^{\circ}\text{C}/\text{decade}$) and 12 months running mean global temperature time series with respect to 1979–1998 (From Wikipedia, Giorgiopp2, GNU Free Documentation license)

trend that is evident in plots of the temperature record. It is also sometimes due to a lack of understanding of how the data are used to derive an annual average temperature.

5.2.3 *Rising Land and Sea Temperatures*

Land temperatures are derived mainly from weather stations located throughout the world on land. Areas with the greatest populations have the most weather stations and as most of the land and population areas of the world are located in the Northern Hemisphere, most of the weather stations are also located in the Northern Hemisphere. Records show that both land and sea are warming.

5.2.4 *Tropospheric Warming and Stratospheric Cooling*

Tropospheric and stratospheric temperatures are central to the problem of greenhouse warming because General Circulation Models (GCMs) predict that temperature changes with enhanced concentrations of greenhouse gases will have a characteristic profile in these layers, with warming in the mid- and lower troposphere and cooling in much of the stratosphere. The cooler stratospheric temperatures would be an expected consequence of the increased trapping of terrestrial radiation in the troposphere.

The illustration above (Fig. 5.3) shows the cooling of the lower stratosphere during the latter part of the twentieth century as directly measured by satellites and weather balloons.

If the stratosphere is cooling, the Sun could not be causing the Earth's global warming. If it was the Sun, the atmosphere would be heating throughout and the stratosphere would be warming as well.

It is harder to measure temperature in the stratosphere than in the troposphere where in the latter there is a network of measurement stations. Stratospheric temperature measurements do exist. They have been made using weather balloons, radiosondes, microwave sounding units (MSUs), rocketsondes (an instrument carried aloft by a rocket), LIDAR (light detection and ranging), and satellites (Fig. 5.3).

5.3 Sources of Uncertainty with Temperature Data

Despite all the attempts to formalize, convert, assimilate, analyse, and reduce the temperature data, problems will always remain, and it is important to be aware of them as discussed in the following sections. Uncertainty is part of science and a good scientist always remains sceptical until experiments and tests have been verified; and this is certainly the case with temperature data.

There are, however, problems inherent in collecting any data from natural systems for any purpose. These problems may be due to any one or all of the following for any natural data set:

- Missing components or errors in the data;
- “Noise” in the data associated with biased or incomplete observations;
- Random sampling error and biases (non-representativeness) in a sample.

There are statistical and other methods of dealing with most of the uncertainty.

The key to understanding global climate change is to first understand what global climate is, and how it operates. It is a complex system involving many variables in time (temporal) and space (spatial) and there are additional sources of uncertainty as follows:

- Ambiguously defined concepts and terminology;
- Inappropriate spatial or temporal units;
- Inappropriateness of or lack of confidence in underlying assumptions;
- Uncertainty due to projections of human behaviour (e.g., future consumption patterns, or technological change), which is distinct from uncertainty due to “natural” sources (e.g., climate sensitivity, chaos).

The global climate system is the result of links and interactions between the atmosphere, oceans, glaciers, living organisms, Earth history, and the solid Earth. Only by considering the climate system in these relationships is it possible to understand the cycles of energy in the atmosphere, an understanding which is required to investigate the causes (and effects) of climatic change.

Because of the convergence of individual elements that make up the climate system, it is appropriate to divide a treatment of the system into separate sections; each section dealing with a different component. This will begin with the atmosphere and its energy budget or energy cycle, the balance of which ultimately controls the global climate. Following this, the other components of the climate system (the

oceans and hydrosphere, cryosphere, biosphere, and geosphere) will be introduced showing how each influences the Earth's energy budget and global climate.

5.4 Climate Construction from Instrumental Data

In order to understand the climate and to gain insight into how it is changing and what may be causing the changes, it is necessary to gather the most accurate data available. The following sections will treat the methods and discuss the accuracy and problems with these data.

The basic elements of climate are temperature, rainfall, humidity, and wind over decades, centuries, thousands, and millions of years. There are instruments to measure these climate elements at present. The thermometer is used today to measure temperature and was developed in the 1600s. To measure climate in the past before instruments were devised, however, proxies (substitutes) must be used. Proxies are indirect ways or substitutes used to measure climate elements prior to the development of instrumentation.

5.5 Measurement of Temperature

The global temperature is determined by data reduction after millions of temperature data points have been assembled. This is a monumental task that is only possible because of increasing computer capability and the dedication of thousands of individuals all over the world.

For temperature records before the advent of the thermometer in the seventeenth century, temperature data must be acquired using proxies. Some of the proxies used for temperature in the distant past are geochemical, such as oxygen and carbon ratios that will be discussed later in the text. Other proxies are derived from such things as tree-rings, stalactites and other cave deposits, ice cores, sediment cores from lakes and the ocean, shells of sea creatures, and boreholes into the solid Earth.

Arctic temperatures in the 1990s reached their warmest level of any decade in at least 2,000 years, research published September 4, 2009 in *Science*, indicates. The study, which incorporates geologic records and computer simulations, provides new evidence that the Arctic would be cooling if not for greenhouse gas emissions that are overpowering natural climate patterns.

The similarity of characteristics among the different paleoclimate (proxy) reconstructions provides confidence in the following important conclusions:

- Dramatic global warming has occurred since the nineteenth century.
- The recent record of warm temperatures in the last 15 years is the warmest on Earth in at least the last 1,000 years, and possibly in the last 2,000 years or further back in Earth's history.
- Temperature proxies (substitutes) are perhaps the best evidence for reconstructing the past history of the planet's climate.

Climate proxies are discussed further in the chapter on paleoclimates.

5.5.1 Global Temperature from Meteorological Stations

The temperature graph given in Fig. 1.1 is a graph of readings taken from meteorological stations worldwide from 1880 to 2010. These are from stations located on land and sea and indicate the warming of the atmosphere just above the surface of the Earth.

A typical land-based meteorological station consists of the following:

- A wind gauge or vane;
- A Sunshine recorder;
- A pyranometer (an instrument for measuring insolation);
- A rain gauge;
- A snow gauge;
- An anemometer (an instrument that measures wind speed);
- A temperature recorder shielded by a cover or shelter.

Global land temperatures are reported by a variety of agencies. Those in the United States, and used worldwide, are reported by the U.S. National Climate Data Center (NCDC), a portion of the National Oceanographic and Atmospheric Administration (NOAA), and NASA's Goddard Institute of Space Studies (GISS). These reports are based on the Global Historical Climate Network (GHCN version 3 data). The Global Historical Climatology Network (GHCN) is a database widely used by climate scientists for temperature, precipitation and pressure records managed by the NCDC, Arizona State University, and the Carbon Dioxide Information Analysis Center. Other reporting centers are the U.K.'s Hadley Centre and the Climate Research Unit at the University of East Anglia.

Most of the land records used in calculating the global averages comes from weather stations but some comes from boreholes drilled into the Earth. The latter have only century resolution, at best.

The global land surface temperature was the warmest on record for March 2011, 3.3°F above the twentieth century mean of 40.8°F, for a global average temperature of 44.1°F for March 2011. Temperatures more than 8°F above average covered much of the Asian continent. Two months after the greatest January snow cover extent on record on the Eurasian continent, the unusually warm temperatures led to rapid snow melt, and the March 2011 snow cover extent on the Eurasian continent was the lowest on record.

5.6 The Berkeley Earth Surface Temperature (BEST) Study

The Berkeley Earth Surface Temperature (BEST) study set out to develop a new method of obtaining a land surface average temperature and compare it with existing studies that have been done by U.S. and U.K. Governmental agencies. The study was led by a University of California (Berkeley) physicist who was described as a climate change/global warming skeptic prior to the study.

The BEST study used over 39,000 unique stations which are more than five times the 7,280 stations found in the Global Historical Climatology Network Monthly data set (GHCN-M). Some of the final results of the study are shown in Fig. 5.4.

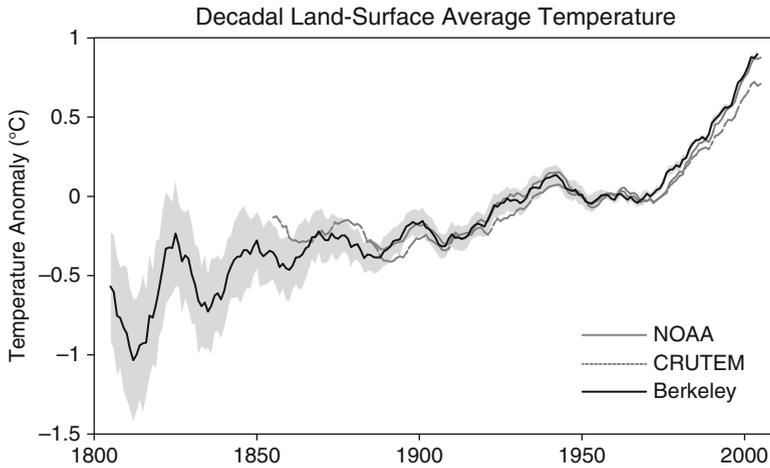


Fig. 5.4 Results of the BEST study. Temperature records constructed by NASA/GISS, NOAA, HadCRU, and UC Berkeley, the latter conducted by a team of University of California Berkeley researchers, has investigated 1.6 billion meteorological records. The data come from 5 times as many stations as in the previous studies. The researchers find exactly the same quantitative results for global temperature rise. The above graph shows the decadal land-surface average temperature using a 10-year moving average of surface temperatures over land. Anomalies are relative to the Jan 1950–December 1979 mean. The *grey band* indicates 95% statistical and spatial uncertainty interval (Based on data from <http://www.berkeleyearth.org/analysis>)

The Berkeley Earth Surface Temperature Study has created a preliminary merged data set by combining 1.6 billion temperature reports from 15 preexisting data archives.

The BEST study addressed scientific concerns raised by skeptics and deniers including urban heat island effect, poor station quality, and the risk of data selection bias. The BEST group concluded that the warming trend is real, that over the past 50 years the land surface has warmed by 0.911°C , and their results mirror those obtained from earlier studies carried out by the U.S. National Oceanic and Atmospheric Administration (NOAA), the U.K.'s Hadley Centre, NASA's GISS Surface Temperature Analysis, and the Climatic Research Unit (CRU) at the University of East Anglia in the U.K. The BEST study also found that the urban heat island effect and poor station quality did not bias the results obtained from these earlier studies.

5.7 Land Temperatures from Boreholes

A global temperature reconstruction using temperatures measured from boreholes was begun and has been maintained by the Geothermal Laboratory at the University of Michigan (also maintained at the NCDC). In the UM study, underground temperature measurements were examined from a database of over 350 boreholes in eastern North America, Central Europe, Southern Africa and Australia (There are 116 sites in eastern North America, 98 in central Europe, 86 in southern Africa, and 58 in Australia). Using this approach, scientists found that the twentieth century was

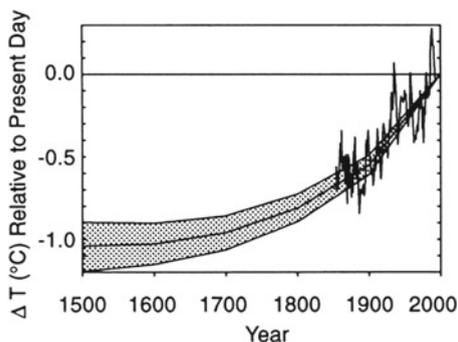


Fig. 5.5 Composite surface temperature change over the past five centuries, relative to the present, as determined from geothermal data. *Shaded areas* represent ± 1 standard error about the mean history. Superimposed is a smoothed (5-year running average) SAT instrumental record (10) representing a composite of the same regions as the geothermal data. Because the SAT series is referenced to the mean anomaly over the interval from 1961 to 1990 and because the geothermal result is referenced to the present, we have shifted the SAT series downward by 0.2°C to enable a visual comparison of the trends by a direct overlay (Modified from Pollard 2005; <http://www.ncdc.noaa.gov/paleo/paleo.html>, Public Domain)

the warmest of the past five centuries, thus confirming the results of surface temperature studies.

The geophysical methods used to generate borehole temperature reconstructions do not permit annual or decadal resolution, but only the century-scale trend in temperatures over the last several centuries. Nonetheless, this record, totally independent of data and methods used in other studies, shows that the Earth has been warming dramatically for some time.

A composite temperature history for 358 borehole sites obtained by University of Michigan scientists from all over the world indicates that the present-day mean temperature of these sites is about 1.0°C warmer, on average, than five centuries ago. The change of temperature in the twentieth century alone has been about 0.5° and equals the cumulative change that is inferred for the previous four centuries. The temperature of the twentieth century appears to be warmer than the mean temperature of any of the previous four centuries. The composite meteorological record for the sites, where available, displays similar trends in the time interval of overlap (Fig. 5.5).

More information on land temperatures from boreholes can be found at the following web site: <http://www.ncdc.noaa.gov/paleo/paleo.html>.

5.8 Rising Sea Temperatures

Sea water responds more slowly to temperature changes than does air or land and the World Ocean is the greatest reservoir of heat on the planet. Global warming caused by human activities that emit heat-trapping carbon dioxide has raised the average global air temperature by about 1°F over the past century. In the oceans, this

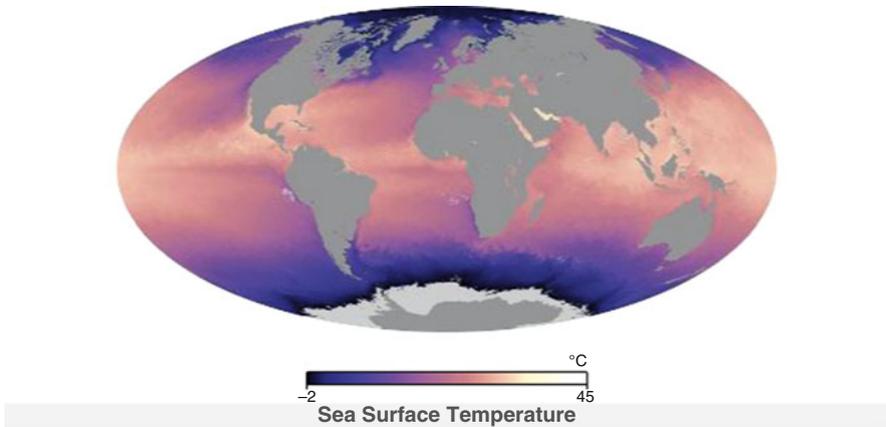


Fig. 5.6 Sea surface temperature distribution throughout the globe (From <http://earthobservatory.nasa.gov/GlobalMaps/view.php?d1=MYD28M>, Public Domain)

change has only been about 0.18°F. This warming has occurred from the surface to a depth of about 2,300 ft (700 m), where most marine life exists.

The ocean has an important role in climate variability and change. The ocean's heat capacity is about 1,000 times larger than that of the atmosphere, and the oceans net heat uptake since 1960 is around 20 times greater than that of the atmosphere. This large amount of heat, which has been mainly stored in the upper layers of the ocean, plays a crucial role in climate change, in particular variations on seasonal to decadal time scales. As the ocean warms it also causes sea level to rise due to thermal expansion and if ocean waters continue to warm there are severe consequences for the world's food chain.

5.8.1 *Relative Distribution of Sea-Surface Temperatures (SSTs)*

The current relative distribution of sea-surface temperatures is shown in Fig. 5.6. Sea surface temperatures across the globe have a large influence on climate and weather patterns. For example, every 3–7 years a wide swath of the Pacific Ocean along the Equator warms by 2–3 °C. This warming is a hallmark of the climate pattern of El Niño, which changes rainfall patterns around the globe, causing heavy rainfall in the southeastern United States and severe drought in Australia, Indonesia, and southern Asia. On a smaller scale, ocean temperatures influence the development of tropical cyclones (hurricanes and typhoons), which draw energy from warm ocean waters to form and intensify. There is a direct relationship between the strength of the El Niño and the number of storms and storm intensities.

The sea surface temperature map shown in Fig. 5.6 is based on observations by the Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's Aqua satellite. The satellite measures the temperature of the top millimeter of the ocean surface. In this map, the coolest waters appear in blue (approximately -2°C or

28.4°F), and the warmest temperatures appear in pink-yellow (45 °C or 113 °F). Land masses and the large area of sea ice around Antarctica appear in shades of gray, indicating no data were collected.

The most obvious pattern shown in a time series (which can be downloaded from the NASA web site for their Earth Observatory information at <http://earthobservatory.nasa.gov/GlobalMaps/view.php?d1=MYD28M>), is the year-round difference in sea surface temperatures between Equatorial regions and the poles. Various warm and cool currents stand out even in monthly averages of sea surface temperature. A band of warm waters flows up the East Coast of the United States and then across the North Atlantic – the well-known Gulf Stream.

Although short-lived weather events that influence ocean temperature are often hidden in monthly averages, a few events do show up. For example, in December 2003, strong winds blew southwest from the Gulf of Mexico over Central America toward the Pacific Ocean, driving warm surface waters away from the coast and allowing cold water from deeper in the ocean to rise up to the surface. These winds are a recurring phenomenon in the area in winter; they are known as Tehuano winds.

5.8.2 Ocean Heat Content

Approximately 93.4% of the Earth’s heat buildup has gone into the World Ocean. How does the ocean gain heat? Climate scientists and oceanographers like to think of the ocean as having a “skin” which is the upper few millimeters to a few meters of the ocean. The “skin” is warmed by sunlight and the heat begins to move downward to deeper ocean waters. Therefore, as stated by the Second Law of Thermodynamics, as sunlight continues to heat the ocean surface, heat moves into the atmosphere if the latter is cooler, down into the deeper ocean water which is also cooler, and is dispersed in all directions by ocean currents.

It has been documented that warmer waters in the Southern Ocean (around Antarctica) are melting glacial ice from the west coast of Antarctica. The warming waters of the Southern Ocean are melting ice from the west Antarctic ice shelves. As these ice shelves melt, additional ice moves from the continent to replace them as ice shelves and this leads to additional sea level rise.

The illustration below (Fig. 5.7) shows the increasing heat content in the first 700 m of ocean waters from the 1950s through 2009. It is in the first 700 m of the World Ocean where most oceanic life exists. There is little doubt where most of Earth’s heat buildup is occurring; it is occurring in the World Ocean.

5.9 Melting Ice

The majority of ice is found in nature as glaciers, ice sheets, sea ice, permafrost, and on the bottom of the ocean in methane clathrates. It is also found on lakes and streams during colder parts of the year in mid-latitudes and higher elevations, as

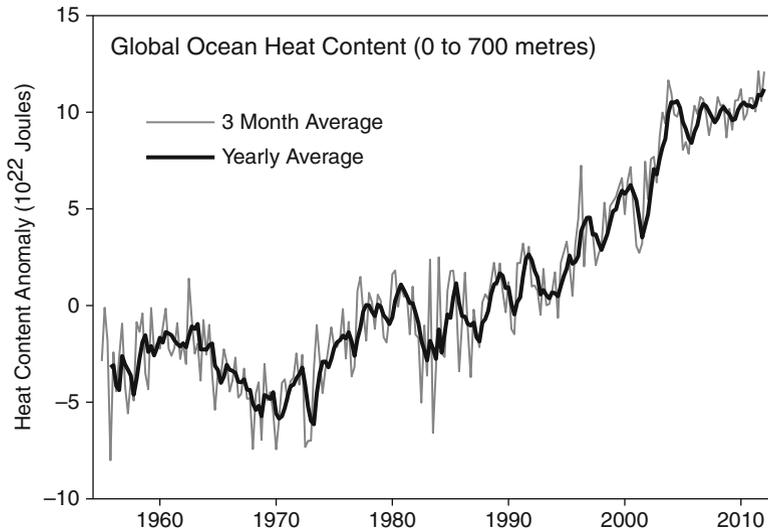


Fig. 5.7 Global ocean heat content (From http://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/; updated from Levitus et al. 2009, Public Domain)

icebergs in the ocean, and as ice shelves and ice caps. Most of this ice is melting, some more rapidly than others. Ice may even be expanding due to local conditions in some locations and in different times of the year but the diminishing trend of ice on Earth is apparent.

There has been debate over the glaciers in the Himalayan Mountains since an error was discovered in the thousands of pages of the IPCC AR4 report of 2007. The report stated that the Himalayan glaciers were disappearing at a faster rate than was actually happening. This error was corrected by the IPCC but some critics have not given up on their attacks of the 2007 report. The Himalayan glaciers are receding in their lower reaches but some may actually be gaining ice at higher elevations. Those in the highest elevations will take much more warming to recede as temperatures at higher elevations are lower and the majority of precipitation falls as snow.

The IPCC AR4 2007 report consisted of four major sections with numerous supplementary reports. These sections are as follows:

- Contribution of Working Group I (WGI): *Climate Change 2007: The Physical Science Basis*.
- Contribution of Working Group II (WGII): *Climate Change 2007: Impacts, Adaptation and Vulnerability*.
- Contribution of Working Group III (WGIII): *Climate Change 2007: Mitigation of Climate Change*.
- Contribution of Working Groups I, II, and III: *The Synthesis Report (SYR)*.

The IPCC AR4 2007 report, *Climate Change 2007: The Physical Science Basis*, assessed current scientific knowledge of “the natural and human drivers of climate

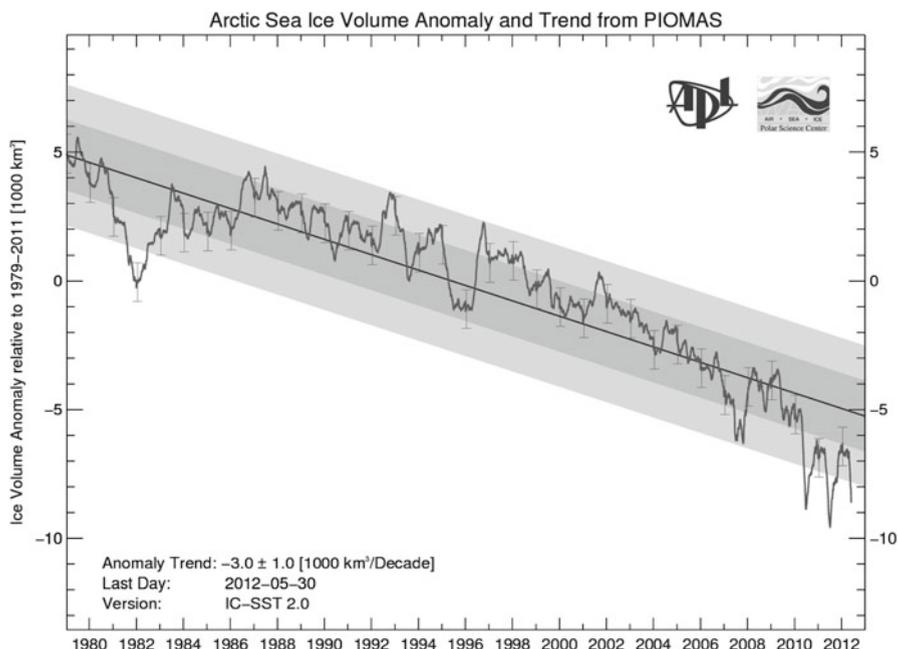


Fig. 5.8 Arctic sea ice volume anomaly from Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) updated once a month. Daily Sea Ice volume anomalies for each day are computed relative to the 1979–2010 average for that day of the year. The trend for the period 1979–present is shown in blue. *Shaded areas* show one and two standard deviations from the trend. *Error bars* indicate the uncertainty of the monthly anomaly plotted once per year (From Polar Science Center, <http://psc.apl.washington.edu/wordpress/>, viewed 12/28/2011; work supported by U.S. Public funds, Public Domain)

change” as well as observed changes in climate. It looked at the ability of science to attribute changes to different causes, and made projections of future climate change.

The *Physical Science Basis* was produced by 676 authors (152 lead authors, 26 review editors, and 498 contributing authors) from 40 countries, and then reviewed by over 625 expert reviewers. More than 6,000 peer-reviewed publications were cited. It is amazing that only two mistakes have been found.

Before being approved, the summary was reviewed line by line by representatives of 113 governments during the 10th session of WGI, in January to February 2007.

Further discussion of the reports can be found throughout this text.

The illustration above (Fig. 5.8) shows the decline in Arctic sea ice volume since 1979 through 11-30-2011.

Arctic ice has undergone a steady decline in extent while Antarctic sea ice has apparently increased. Does this mean that the Antarctic is cooling thereby forming new sea ice? Not necessarily, because sea ice is frozen water and its extent may be deceptive. It is possible to have global warming and expanding sea ice if the volume

of ice throughout the globe is decreasing. Extent is not necessarily related to volume. New ice may be forming on the ocean surface while old ice is being reduced in volume, as is happening in both the Arctic and Antarctic.

Arctic sea ice thickness comparisons over time are given in a fairly recent study. This study examined sea ice thickness records from submarines and ICESat (NASA's Ice, Cloud and Elevation satellite) observations from 1958 to 2008 (ICESat's laser altimeter). Examining 42 years of submarine records (1958–2000), and 5 years of ICESat records (2003–2008), scientists determined that mean Arctic sea ice thickness declined from 3.64 m in 1980 to 1.89 m in 2008, a decline of 1.75 m.

Another recent study (February 2012) shows that the oldest and thickest Arctic sea ice is disappearing at a faster rate than the younger and thinner ice at the edges of the ice cap. The rapid disappearance of older ice makes the Arctic Ocean's sea ice cap more vulnerable to further decline.

The thickest “multi-year” ice survives through two or more summers, while young, seasonal ice forms over a winter and typically melts just as quickly as it formed. Scientists also describe a third category; “perennial” ice is all ice cover that has survived at least one summer. All multi-year ice is perennial ice, but not all perennial ice is multi-year ice.

5.9.1 *Permafrost, Methane, and Clathrates*

Vast areas of higher latitudes and high altitudes have permanently frozen ground or permafrost. In such areas, the upper few inches of permafrost melt during the warmer seasons of the year and the resulting layer is called the active zone. The active zone causes problems with buildings, roads, and other human-made structures in regions of permafrost.

Permafrost traps a huge quantity of methane (CH_4) in the frozen soils. The methane forms as a product of bacterial activity and is released upon thawing. Methane releases have been occurring recently and there are eyewitness reports from permafrost areas of the world, especially on the North Slope of Alaska and off the coast of Siberia, of methane bubbling up through sea water and lakes.

The Arctic Ocean is underlain by vast deposits of methane in the form of methane clathrates (Fig. 5.9). As the Arctic is warming faster than the rest of the world, it is only a matter of time before this methane is released to the atmosphere. The majority of the methane accumulated in what is now shallow ocean water during the last glacial maximum (LGM) about 18,000 years ago during the low stand of sea level. As these massive sheets of ice receded, sea level rose and these areas have become the world's shallow seas bordering the continents today (see Fig. 5.9).

Before the coastal areas of the world became completely drowned by rising sea level during the melting of the last continental glaciation, they were salt or tidal marshes in which anaerobic (oxygen-free) bacteria were breaking down complex hydrocarbons to methane. In dry conditions there is plenty of atmospheric oxygen, and so aerobic bacteria which produce carbon dioxide (CO_2) are preferred. But in wet areas such as

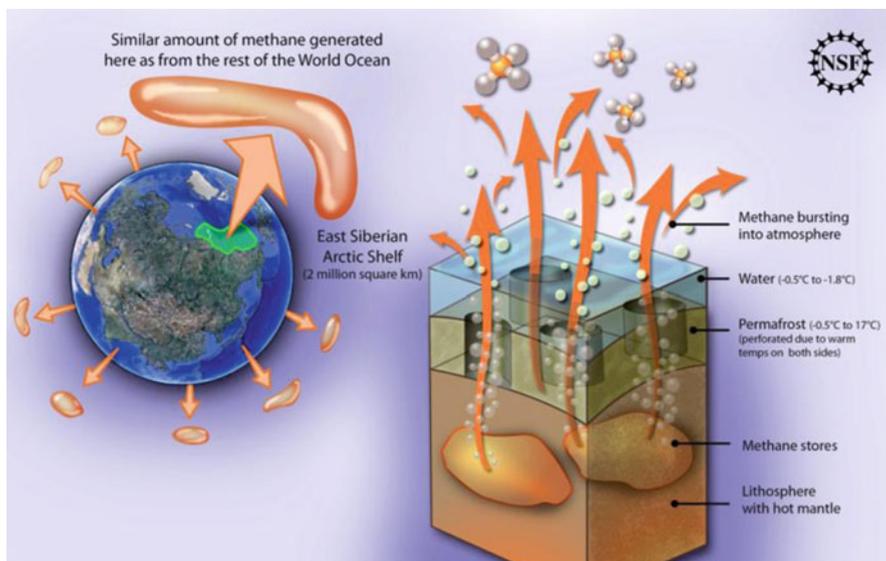


Fig. 5.9 Methane clathrates in the shallow Arctic ocean (National Science Foundation, Public Domain, from (<http://www.theresilientearth.com/?q=content/arctic-armageddon-or-methane-madness>))

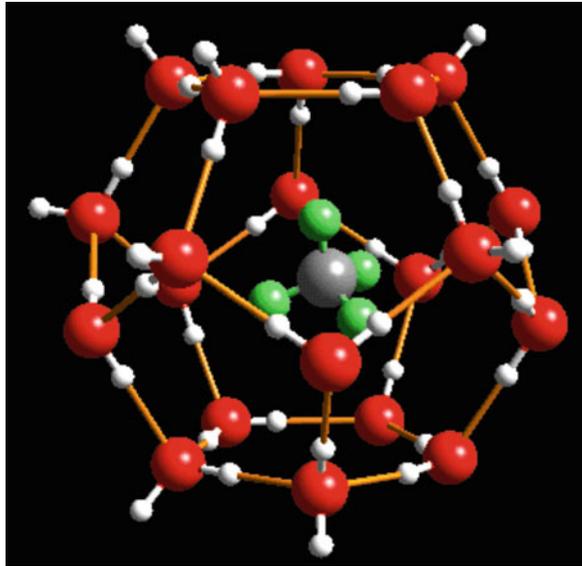
swamps, wetlands and in parts of the ocean, there is not enough oxygen so complex hydrocarbons get broken down to methane by anaerobic bacteria. Some of this methane gets trapped and some makes its way into the atmosphere where it is gradually broken down to CO_2 and water (H_2O) vapor in a series of chemical reactions.

5.9.2 Methane Clathrates

Clathrates are a type of compound structure that consists of a cage of molecules that can trap gases, such as methane, in a solid form (Fig. 5.10).

For methane, the most important cage is one that is made of water molecules, and so is erroneously described sometimes as a hydrate. Some key facts about clathrates make them particularly interesting to climatologists and climate change scientists. First, they may make up a significant portion of total fossil carbon reserves. Current best estimates suggest that maybe 500–2,000 gigatonnes (1 gigatonne = 1 billion tonnes) of carbon may be stored as methane clathrates (5–20% of total estimated reserves). Some estimates are as high as 10,000 gigatonnes. They occur mainly on the continental shelf where the water is relatively cold; there is sufficient pressure and enough organic material to keep the methane-producing bacteria active. Most importantly, clathrates can be explosively unstable if the temperature increases or the pressure decreases which can happen as a function of climate change (warming),

Fig. 5.10 A model of a methane clathrate showing the cage of H₂O molecules trapping a methane molecule (From http://peggy.uni-mki.gwdg.de/docs/kuhs/clathrate_hydrates.html; **No source information given on web site.** Permission granted by Dr. Werner Kuhs from which the figure is taken)



tectonic uplift, or undersea landslides. A release of methane from clathrates has already begun in shallow waters of the Arctic where methane has been seen as bubbles issuing from lakes and shallow continental shelf areas and near disturbed areas of the Gulf of Mexico, as in the case of the BP oil well blowout in 2010.

There is an imminent danger of additional methane being released from shallow Arctic waters in the near future as oil and natural gas drilling platforms are in progress toward the Arctic as this is being written in June 2012. There are predictions of new reserves of significant quantity to be found off the northern coasts of Alaska, Canada, and Siberia and the real possibility of environmental disasters as new fields are opened in this pristine and fragile area around the North Pole.

5.10 Rising Sea Level

Sea level has been rising over most of the globe since at least 1870. This rise in sea level is not due to the same factors in all places, however. In some areas, the land is sinking which appears to accentuate the rise in sea level. In other areas, land is rising which appears to lessen the rise in sea level. The illustration below (Fig. 5.11) shows the global mean sea level rise from both tide gauges and satellite altimeter measurements. Global sea level actually was lowered during 2011 due to an unusually strong El Niño that increased precipitation over land and caused major flooding in several parts of the world (especially in Australia and Pakistan). There was so much water removed from the World Ocean due to the strong El Niño that sea level worldwide was lowered. However, as can be seen in Fig. 5.11, sea level has begun to rise again.

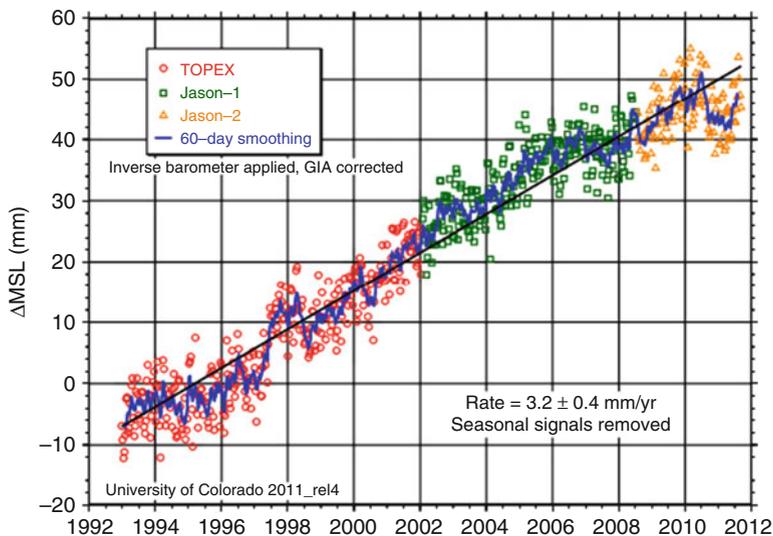


Fig. 5.11 Global mean sea level (GMSL) from 1992 through 2011 (From <http://sealevel.colorado.edu/>; This work was funded by NASA under a OSTM/Jason science investigation. Public Domain)

5.11 Migration of Plants and Animals

Plants and animals are migrating to higher latitudes and altitudes. A recent (2011) study reported in the journal *Science*, which examined roughly 2,000 species, found plants and animals are moving 15 ft per day or about a mile per year away from the Equator at a rate much faster than in previous decades. Species migrated more rapidly from areas most heavily impacted by climate change. Distributions of species have recently shifted to higher elevations at a median rate of 11.0 m per decade, and to higher latitudes at a median rate of 16.9 km per decade.

As the Earth continues to warm, animals and plants continue to migrate. Biologists are concerned that some species will not be able to migrate fast enough, and of course some cannot physically migrate, and whole species will eventually become extinct as rising temperatures exceed their limits of tolerance.

5.12 Species Extinctions

Human beings are currently causing the greatest mass extinction of species since the extinction of the dinosaurs 65 million years ago. If present trends continue it has been estimated that up to one half of all species currently living on Earth will be extinct in less than 100 years as a result of habitat destruction, pollution, invasive species, and

climate change. The extinctions have already begun. Vertebrate species fell by nearly one third between 1970 and 2006, natural habitats are in decline, genetic diversity of crops is falling and 60 breeds of livestock have become extinct since 2000.

In 2010, the United Nations reported that biodiversity on Earth was in trouble; that species were becoming extinct at a rate never before seen in human history. Many of these extinctions, including plants and animals, are occurring in the World Ocean including many organisms that are integral parts of the food chain.

5.13 Human Health Effects of Rising Temperatures

Global warming is already having harmful effects on human health. Climate change poses a serious threat to human health. The World Health Organization (WHO) estimates that since 2000 one million people have been killed directly or indirectly because of our warming planet. This is not including death from air pollution, which kills 800,000 people each year and is expected to worsen with global warming.

As the Earth's temperature increases the seasons are changing especially in the mid-latitudes; spring is coming earlier and fall later almost every year. This increases the growing season for plants increasing the pollen counts in the atmosphere and causing more allergic reactions in humans. Allergic reactions can often lead to respiratory infections and death especially in the very young and very old.

As the climate continues to warm, water and food borne diseases are an increasing problem for human health and the forecast is not good for each of the following:

- According to the U.S. Center for Disease Control (CDC), food borne diseases are responsible for about 76 million cases of illness, with 325,000 hospitalizations and 5,000 deaths in the U.S. every year. Water borne diseases are responsible for about nine million cases of illness every year in the U.S.
- The following diseases can all be transmitted by water and food contamination: *E. coli*, typhoid, hepatitis A, dysentery, cryptosporidiosis, polio, giardia, cholera, and botulism.
- Water treatment facilities have difficulty removing many water borne diseases from drinking water, including cryptosporidiosis and giardia. Contaminated drinking water caused a cryptosporidiosis outbreak where 403,000 people became ill in Madison, Wisconsin in 1993. A CDC report estimated the outbreak cost \$96.2 million: \$31.7 million in medical costs and \$64.6 million in productivity losses.
- Diarrhea, caused mainly by food and water borne diseases, is the second leading cause of death in young children. According to the CDC each year an estimated four billion cases of diarrhea cause two million deaths.

How climate change can increase water and food borne diseases:

- Increase in temperature causes more occurrence/survival of bacteria, toxic algae, and other contamination in food and water. Also, according to the IPCC climate change is already reducing the amount of high quality freshwater and this situation

is expected to worsen. People will be forced to use poorer quality water sources, leading to increased disease.

- The major pathogens that cause acute gastroenteritis multiply faster in warmer conditions. According to a study on climate change impacts on the U.S., this is predicted to impact lakes and increase the number of recreational water borne disease outbreaks.
- Climate change is predicted to cause more extreme flooding and storms, which are known to lead to contaminated water supplies. Heavy rainfall can cause sewer/storm water systems to overflow, releasing raw (untreated) sewerage into local water sources.
- The WHO reported that in 2000 climate change was responsible for approximately 2.4% of worldwide diarrhea. In 2030, warmer temperatures and more severe rainfall and flooding will cause up to a 10% higher risk of diarrhea in some areas.
- According to the IPCC, the distribution and activity of flies, cockroaches, and rodents could change in response to climatic changes. These species are carriers of food-borne pathogens and are considered to be major hygienic pests in the domestic environment.

5.14 Attribution

Attribution is assigning a cause to a result and in climate science as well as in other sciences this may be difficult to do. However, in some cases such as global warming, sometimes it is possible to eliminate natural causes and be left with only human (anthropogenic) causes to explain the result.

In the recent past, variations in the Sun's energy output have regulated the Earth's temperature to a great degree. Scientists know that the Sun today is warmer than the Sun of billions of years ago. So can the recent warming on Earth be attributed to the Sun? According to some deniers and skeptics, the answer is yes. However, scientific facts tell us just the opposite: no! As a matter of fact, since the 1970s to 2011 and into 2012, the Sun has been in a deep stage of its solar minimum phase. In other words, the Sun has been producing less energy while the Earth has been warming (Fig. 5.12).

As can be seen in Fig. 5.12, there was a fairly good correlation between solar activity and the Earth's temperature until around 1980, then the two began to diverge, and they have been diverging until fairly recently.

If the Sun is not causing the Earth to warm, what is causing global warming? What other things could cause the Earth to warm? Let's look at some other possibilities:

- The Earth may be moving closer to the Sun in its orbit;
- The Sun may be moving closer to the Earth;
- The Earth may be heating up from the inside;
- Another star, like the Sun, may be moving closer to Earth;

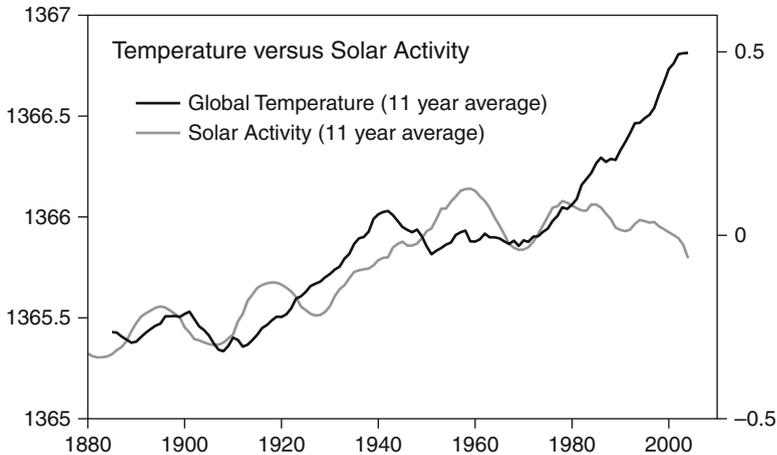


Fig. 5.12 Global temperature (*dark line*, NASA GISS) and Total solar irradiance (*lighter line*, 1880–1978 from Solanki); 1979–2009 from Physikalisch-Meteorologisches Observatorium Davos (PMOD). (From SkepticalScience.com, redrawn by John Cook)

- The temperature record may be unreliable;
- Something in the atmosphere may be holding more heat close to the Earth rather than letting it escape into space.

Astronomers tell us that the orbits of Earth and the other planets in the Solar System have very stable and predictable orbits and these have not deviated substantially in recorded history. So the Earth is not moving closer to the Sun and the Sun is not moving closer to the Earth.

Geologists and geophysicists tell us that although the Earth has a great deal of internal heat that this heat is not expanding outward. So the Earth's surface and lower atmosphere are not heating up from the inside.

No star is moving closer to Earth and if it were it would be so far away at present to have no effect on the Earth's temperature.

Is there something in the atmosphere that may act to contain heat and possibly re-radiate heat back to the Earth's surface? Remember the greenhouse effect from Chap. 2? It is now time for some chemistry as it is chemicals that cause the greenhouse effect.

5.15 Greenhouse Gases

There are chemicals in Earth's atmosphere that are greenhouse gases (GHGs) that trap heat and allow the Earth to support life. The main GHGs are water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). Other minor greenhouse gases are such things as chlorofluorocarbons (CFCs) and a few others. Their increasing concentrations in the atmosphere are shown in Fig. 5.13.

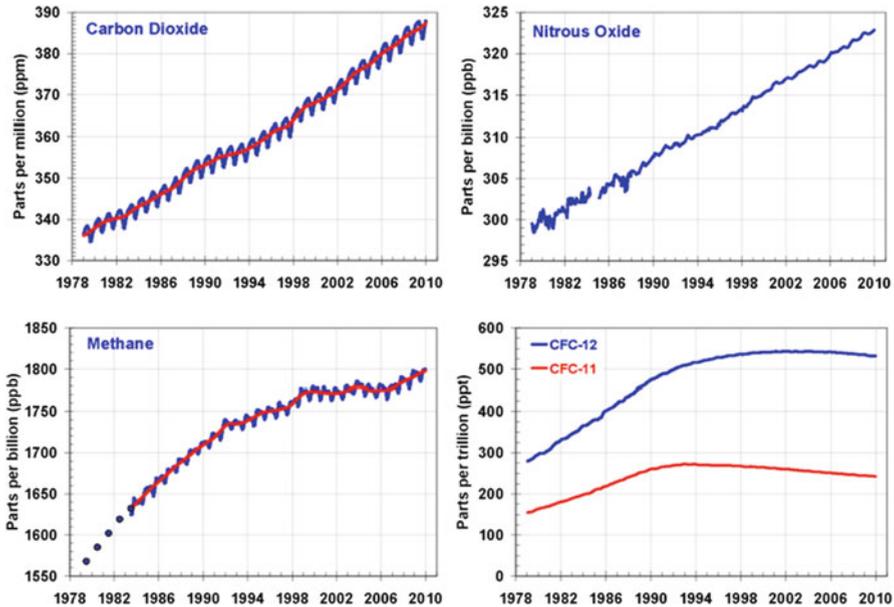


Fig. 5.13 Greenhouse gases increasing in the atmosphere since 1978 (From NOAA <http://www.esrl.noaa.gov/gmd/aggi/>, Public Domain)

Carbon dioxide, nitrous oxide, and methane appear to have been steadily increasing while the CFCs appear to be leveling off or slightly decreasing in Earth's atmosphere (Fig. 5.13). Greenhouse gases appear to be good candidates for causing global warming and they will be treated separately in a later chapter (Chap. 9).

The observed patterns of warming, including greater warming over land than over the ocean, and their changes over time, are simulated only by models that include anthropogenic forcing. No coupled global climate model that has used natural forcing only has reproduced the continental mean warming trends in individual continents (except Antarctica) over the second half of the twentieth century.

The illustration below (Fig. 5.14) shows time series of global mean near-surface air temperature anomalies in observations and simulations by using a Canadian computer model (CanESM2). In Fig. 5.14a all of the observations and simulations are graphed together from 1850 to 2011. In the illustration, black lines show observed global mean annual temperature from HadCRUT3, and thin colored lines show global mean temperature from five-member ensembles of CanESM2 forced with (a) anthropogenic and natural forcings (ALL), (b) natural forcings only (NAT), (c) greenhouse gases only (GHG), and (d) aerosols only (AER). All anomalies are calculated relative to the period 1851–1900, and ensemble means are shown by thick colored lines in the figure.

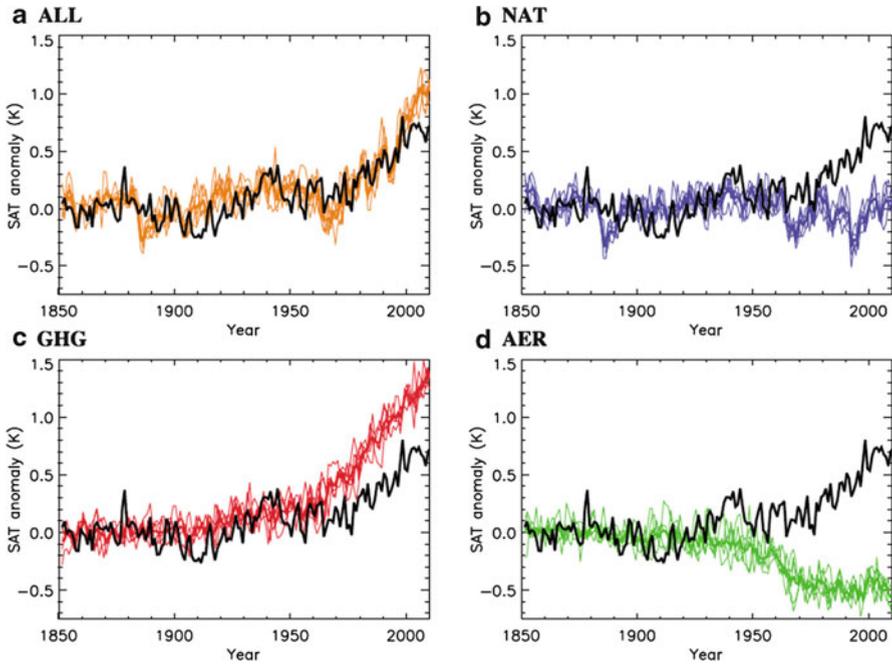


Fig. 5.14 Time series of global mean near-surface air temperature anomalies in observations and simulations of CanESM2. *Black lines* show observed global mean annual mean temperature from HadCRUT3, and *thin coloured lines* show global mean temperature from five-member ensembles of CanESM2 forced with (a) anthropogenic and natural forcings (ALL), (b) natural forcings only (NAT), (c) greenhouse gases only (GHG), and (d) aerosols only (AER). All anomalies are calculated relative to the period 1851–1900, and ensemble means are shown by *thick coloured lines* (From SkepticalScience.com, viewed 1/14/2012; data from Gillett et al. 2012)

5.16 Human Fingerprints on Global Warming

There are specific human fingerprints on the current warming of the planet. The human fingerprints point directly to humankind as the source for the vast majority of the global warming that has occurred during the latter half of the twentieth century and into the twenty-first.

5.16.1 Earth's Cooling Upper Atmosphere

As more heat is added to the lower atmosphere (the troposphere), less heat escapes to warm the upper atmosphere (the stratosphere) and the upper atmosphere cools. This has been measured by satellites and weather balloons (radiosondes). If the Sun was the cause of global warming, the upper atmosphere would also be warming.

5.16.2 Rising Tropopause

As the troposphere warms the air expands and the top of the troposphere (the tropopause) rises. Scientists have found that the tropopause from 1979 to 1999 had risen by about 200 m. The rising tropopause is caused by the increasing heat of the troposphere.

5.16.3 Less Heat Escaping to Space

Satellites measure less heat escaping to space at the particular wavelengths that CO₂ absorbs heat, thus finding “direct experimental evidence for a significant increase in the Earth’s greenhouse effect.” Skeptics and deniers of global warming say that there is no evidence that CO₂ is causing global warming. This empirical fact proves that CO₂ is causing global warming.

5.16.4 Nights Warming Faster than Days

If an increased greenhouse effect is causing global warming, we should see certain patterns in the warming. For example, the planet should warm faster at night than during the day. This is indeed being observed.

5.16.5 Winter Warming Faster than Summer

Temperatures from both Northern and Southern Hemispheres show winters warming faster than summer based on both land and sea records and satellite records.

5.16.6 More Fossil Fuel Carbon in Coral

The most common carbon isotope is carbon-12 (¹²C) which is found in roughly 99% of the carbon dioxide in the atmosphere. The slightly heavier carbon-13 (¹³C) makes up most of the rest. Plants prefer carbon-12 over carbon-13. This means the ratio of carbon-13 to carbon-12 is less in plants than it is in the atmosphere. As fossil fuels originally come from plants, it means when we burn fossil fuels, we’re releasing more ¹²C into the atmosphere. If fossil fuel burning is responsible for the rise in atmospheric CO₂ levels, we should be seeing the ratio of ¹³C to ¹²C decrease. This decrease in the ratio is exactly what is being recorded.

5.16.7 Shrinking Upper Atmosphere

The thermosphere and ionosphere are shrinking as measured by satellites. The ionosphere is expected to cool and contract in response to greenhouse warming. This has been observed by satellites.

5.16.8 Less Oxygen in the Atmosphere

Oxygen levels are falling in line with the amount of carbon dioxide rising, just as one would expect from fossil fuel burning which takes oxygen out of the air to create carbon dioxide.

5.16.9 More Fossil Fuel Carbon in the Atmosphere

See “More Fossil Fuel Carbon in Coral” above.

5.16.10 More Heat Returning to Earth

Less heat is escaping to space; so where is it going? It is being reflected back to the Earth’s surface. Surface measurements confirm this, observing more downward infrared radiation. A closer look at the downward radiation finds more heat returning at CO₂ wavelengths, leading to the conclusion that “this experimental data should effectively end the argument by skeptics that no experimental evidence exists for the connection between greenhouse gas increases in the atmosphere and global warming.”

5.16.11 Pattern of Ocean Warming

Ocean heat content has increased significantly over the past 40 years. In fact, approximately 93% of the total heating of the Earth system over that period has gone into warming the oceans. Barnett et al. (2005) investigated the cause of this warming signal, and concluded as follows:

“[The increase in ocean heat content] cannot be explained by natural internal climate variability or solar and volcanic forcing, but is well simulated by two anthropogenically forced climate models. We conclude that it is of human origin, a conclusion robust to observational sampling and model differences. Changes in advection combine with surface forcing to give the overall warming pattern. The implications of this study suggest that society needs to seriously consider model predictions of future climate change”.

Humans are currently emitting several billion tonnes (1 billion tonnes is a gigatonne, a tonne is equal to a metric ton which is a unit of weight equal to 1,000 kg, or 2,204.6 lb) of CO₂ into the atmosphere every year. Of course, it could be a coincidence that CO₂ levels are increasing so sharply at the same time as the Earth's temperature is rising so let's look at more evidence that humans are responsible for the rise in CO₂ levels and global warming. Correlation does not mean cause and effect but in science, when several independent lines of evidence point to the same conclusion, scientists may draw conclusions with a great deal of certainty.

When measuring the type of carbon accumulating in the atmosphere, we see more of the type of carbon that comes from fossil fuels. Carbon from fossil fuels has no carbon-14, radioactive carbon or radiocarbon. Radiocarbon has a half-life of 5,700 years and very little if any is remaining in fossil fuels because most fossil fuels are millions of years old.

Scientists know how much carbon-14 is in the atmosphere relative to non-radioactive carbon. As the ratio of carbon-14 to non-radioactive carbon decreases, the indication is that non-radioactive carbon is being released. The main source of this release is the burning of fossil fuels.

Human fingerprints are indicated by measurements of oxygen in the atmosphere. Oxygen levels are falling in line with the amount of carbon dioxide rising, just as one would expect from fossil fuel burning which removes oxygen from the atmosphere to create carbon dioxide. For every atom of carbon in the molecule of carbon dioxide, there are two oxygen atoms.

Further independent evidence that humans are raising CO₂ levels comes from measurements of carbon found in coral records going back several centuries. These coral skeletons show a recent sharp rise in the type of carbon that comes from fossil fuels.

We know humans are raising CO₂ levels because of the type of carbon being released and because we are able to measure it directly. Also, satellites measure less heat escaping out to space at the particular wavelengths that CO₂ absorbs heat, thus finding "direct experimental evidence for a significant increase in the Earth's greenhouse effect."

If less heat is escaping to space, where is it going? It is being reflected back to the Earth's surface. Surface measurements confirm this, observing more downward infrared radiation. A closer look at the downward radiation finds more heat returning at CO₂ wavelengths leading to the conclusion that "this experimental data should effectively end the argument by skeptics that no experimental evidence exists for the connection between greenhouse gas increases in the atmosphere and global warming."

If an increased greenhouse effect is causing global warming, we should see certain patterns in the warming. For example, the planet should warm faster at night than during the day. This is indeed being observed.

Another distinctive pattern of greenhouse warming is cooling in the upper atmosphere, otherwise known as the stratosphere. This is exactly what's happening.

With the lower atmosphere (the troposphere) warming and the upper atmosphere (the stratosphere) cooling, another consequence is the boundary between the troposphere and stratosphere, otherwise known as the tropopause, should rise as a consequence of greenhouse warming. This has been observed.

An even higher layer of the atmosphere, the ionosphere, is expected to cool and contract in response to greenhouse warming. This has been observed by satellites.

Components of the Climate Change Process

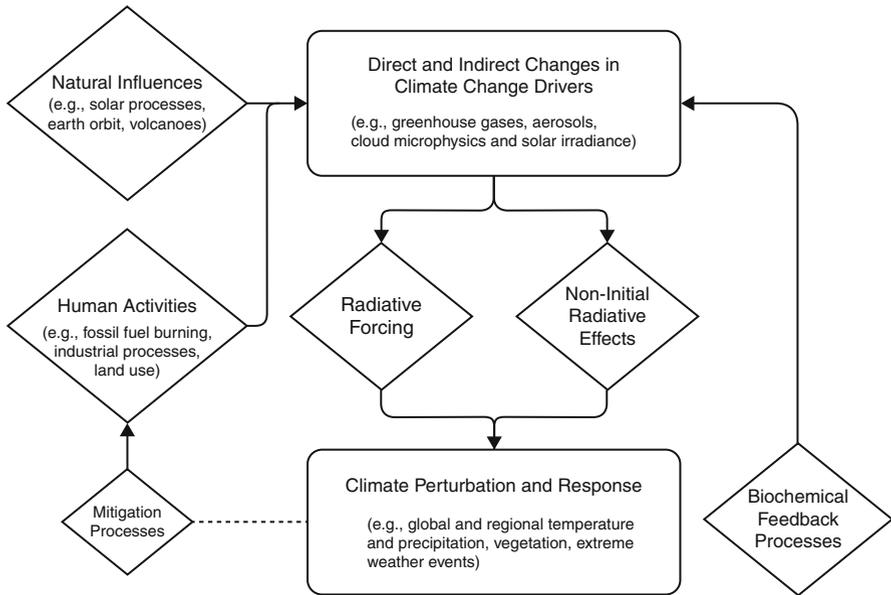


Fig. 5.15 Components of the climate change process (Redrawn from IPCC, AR4, 2007 by John Cook)

Science proceeds by gathering evidence. It isn't a house of cards, ready to topple if you remove one line of evidence. Instead, it's like a complex puzzle. As the body of evidence builds, we get a clearer picture of what's driving our climate. We now have many lines of evidence all pointing to a single, consistent answer.

The main cause of global warming is increasing carbon dioxide levels from fossil fuel burning. Nothing else makes sense or fits all the facts; and this conclusion is backed by numerous lines of evidence.

Earth's climate is changing. Some of this change is gradual and cannot be detected on a day-to-day basis, such as the global increase in temperature or the gradual melting of glacial ice and rising sea level. Other climate changes are more obvious, such as changing weather patterns, more severe and more frequent storms, or longer hot spells or cold periods. And climate change will become even more obvious in the future as weather patterns continue to change.

5.17 Components of the Climate Change Process

Components of the climate change process are shown in the illustration above (Fig. 5.15). When the drivers of climate are forced in one direction, the climate changes in that direction. For example, when volcanoes erupt violently they emit

tremendous amounts of solid particles into the atmosphere and these particles block out some of the Sun's rays which causes the Earth to cool. The cooling is said to be a perturbation, which is a response to a forcing and is a result of natural forcing of the climate in the direction of global cooling.

The greatest driver or forcing of Earth's climate has been the amount of sunlight received by the Earth. There is a direct effect on the climate if less sunlight falls on the Earth; the Earth cools. If a greater amount of sunlight impacts the Earth, the Earth warms. So there is a direct effect on the climate by the total amount of sunlight received by the Earth. This is called a radiative forcing due to the fact that the energy causing the climate to change radiates from the Sun. An example of a non-radiative forcing is the cooling caused by violent volcanic eruptions or warming by changes in land use.

Forcings cause the climate to change and a climate change may initiate a feedback that causes the forcing to increase in intensity or decrease and possibly reverse a forcing. These are called positive and negative feedbacks, respectively.

5.18 Other Effects of Global Warming

Global warming, the most obvious climate change happening now, is causing more evaporation to occur from the ocean and soils. This evaporation increases the moisture content of the Earth's atmosphere and dries out the land and vegetation. This moisture must fall to Earth somewhere and it is being measured in increasing rainfall (and snowfall) in some areas. This increased precipitation leads to flooding in some land areas, the breaching of dams and levees, and more natural disasters than before the warming occurred. The drying out of land and vegetation results in more wildfires especially in areas that have experienced long periods of drought.

Some areas that were having normal precipitation are now experiencing less precipitation. More precipitation is falling in some areas and less in other areas. The southwestern U.S. is experiencing a double impact from the changing climate as it is becoming dryer due to the loss of soil moisture and hotter due to a warming climate.

Climate change and global warming are causing more evaporation to occur over the oceans and that results in greater cloud formation. There is more heat energy in the atmosphere available to storm systems and this extra energy causes storms to become more frequent and more intense. It is fairly certain that hurricane Katrina that struck the Gulf Coast of the United States in 2005 was as strong as it was because of the increased temperature of waters in the Gulf of Mexico.

In some areas there is more snowfall in higher elevations and latitudes and more rainfall in lower elevations and latitudes. These are general trends and there are local and regional exceptions, but the general trends are what interest climate change scientists the most.

The most abundant and effective greenhouse gas is water vapor, but it does not stay in the atmosphere for long periods of time. It is flushed out of the atmosphere and falls to Earth as precipitation. Some of the other gases, such as carbon dioxide, remain in the atmosphere for much longer periods of time, possibly thousands of years.

The most important of the greenhouse gases for trapping heat in the atmosphere over long time periods and warming the Earth is carbon dioxide, as we will see in a later chapter. Carbon dioxide is well-mixed in the atmosphere and its molecular structure is such that it both absorbs and re-radiates heat that it traps from the infrared energy given off by the Earth. The carbon dioxide molecules in the atmosphere re-radiate this heat energy in all directions, some to outer space, some to adjacent molecules, and some back to the Earth's surface. The physics of this re-radiation has been known since the 1800s.

5.19 Forcings and Feedbacks in the Climate System

There are factors which cause the Earth's climate system to change, as we have seen. These factors are called forcings because they force a change in Earth's climate. Other factors enhance or retard forcings; these are feedbacks. Both forcings and feedbacks are discussed below.

5.19.1 Forcings

When something forces the Earth's climate to change direction, such as warming or cooling, it is called a forcing. Forcings which directly affect the climate, that is, push it in a certain direction, are:

- Changes in the amount of energy radiated by the Sun. If the Sun produces less energy, it forces the Earth to cool; if it produces more energy, it forces the Earth to warm. The Sun has been in a minimal state for the past several decades until recently (October 2011). During Solar Maximum, huge sunspots and intense solar flares are a daily occurrence. Auroras appear in Florida. Radiation storms knock out satellites. Radio blackouts frustrate ham radio operators. The last such episode took place in the years around 2000–2001. During Solar Minimum, the opposite occurs. Solar flares are almost nonexistent while whole weeks go by without a single, tiny sunspot to break the monotony of the blank sun. This is what we are experiencing now. If the orbital parameters of Earth change, the climate is forced to change. For example, if Earth moves closer to the Sun in its orbit, the Earth warms; if it's orbit moves further away from the Sun, the Earth cools;
- If mountains are uplifted and Earth's plates move, the Earth's atmospheric and oceanic circulation patterns change and the climate changes. This changes the pace of weathering (the breakdown of rocks) which also increases as mountains are uplifted and more rocks are exposed. Weathering takes carbon dioxide out of the atmosphere as the rocks break down and the Earth cools. There is more carbon dioxide stored in rocks of the Earth's crust than anywhere else;
- Increasing greenhouse gases (GHGs) in the atmosphere trap heat to warm the Earth. If these gases increase in concentration in the atmosphere, the Earth warms. If they decrease in concentration the Earth cools.

5.19.2 Positive and Negative Forcing and Their Effects

Anything that causes a climate change is called a forcing. One may think of it as something that is forcing the climate to change. There are forcing agents (such as an increase or decrease in sunlight hitting the Earth) and forcing effects (such as a warming or cooling of the Earth). Forcings may either be positive or negative (Fig. 5.16). Figure 5.16a shows the cumulative positive greenhouse gases forcing agents from 1950 through 2004. Figure 5.16b shows the cumulative negative forcing agents over the same time period.

Forcings may occur suddenly or over a few hundred or hundreds of thousands of years. A near collision with another planet in the early development of Earth may have forced the Earth to gain an axial tilt. This would have happened suddenly and the result of the axial tilt is the seasonal changes which occur in middle latitudes each year (summer, winter, fall, and spring).

Figure 5.17 is a diagrammatic representation of the Earth's climate system from pole (on the left side) to Equator (on the right side) showing interactions between the Sun's energy, the atmosphere, oceans, ice sheet, vegetation, back radiation, weathering, greenhouse gases, volcanoes, wind, precipitation, river runoff, etc.

5.19.3 Feedbacks

Forcings cause changes in the climate system and feedbacks either enhance a forcing (positive feedback) or dampen or reverse a forcing (negative feedback).

Feedbacks may also be a forcing. For example, a greenhouse gas may be a forcing when it increases in the atmosphere to the extent that it forces the climate to change. Carbon dioxide has built up in the atmosphere since the Industrial Revolution, the mass production of the internal combustion engine, and because of other human activities. As this concentration increased, it forced the Earth's climate to begin to warm after the Earth's temperature had been relatively stable for thousands of years. After the initial forced warming, carbon dioxide continues to build in the atmosphere and has become a positive feedback as well as a positive forcing. A positive forcing is defined as one which causes warming. A negative forcing is defined as one which causes cooling.

Oceans cover about 71% of Earth's surface area and are a significant part of the climate system. Sea water absorbs energy from both the Sun and the Earth's interior. Colder sea water absorbs CO₂ from the atmosphere and warm sea water releases it to the atmosphere (a carbon source). As ocean waters warm, they will change from a carbon dioxide sink to become a source and release CO₂ to the atmosphere in greater quantities than the world has ever known.

Feedbacks are secondary effects on the climate system (see Fig. 5.18). For example, if there is more melting of glacial and sea ice, there is more land and darker ocean to absorb energy from the Sun, less Sunlight is reflected back to space by the ice, and the Earth warms.

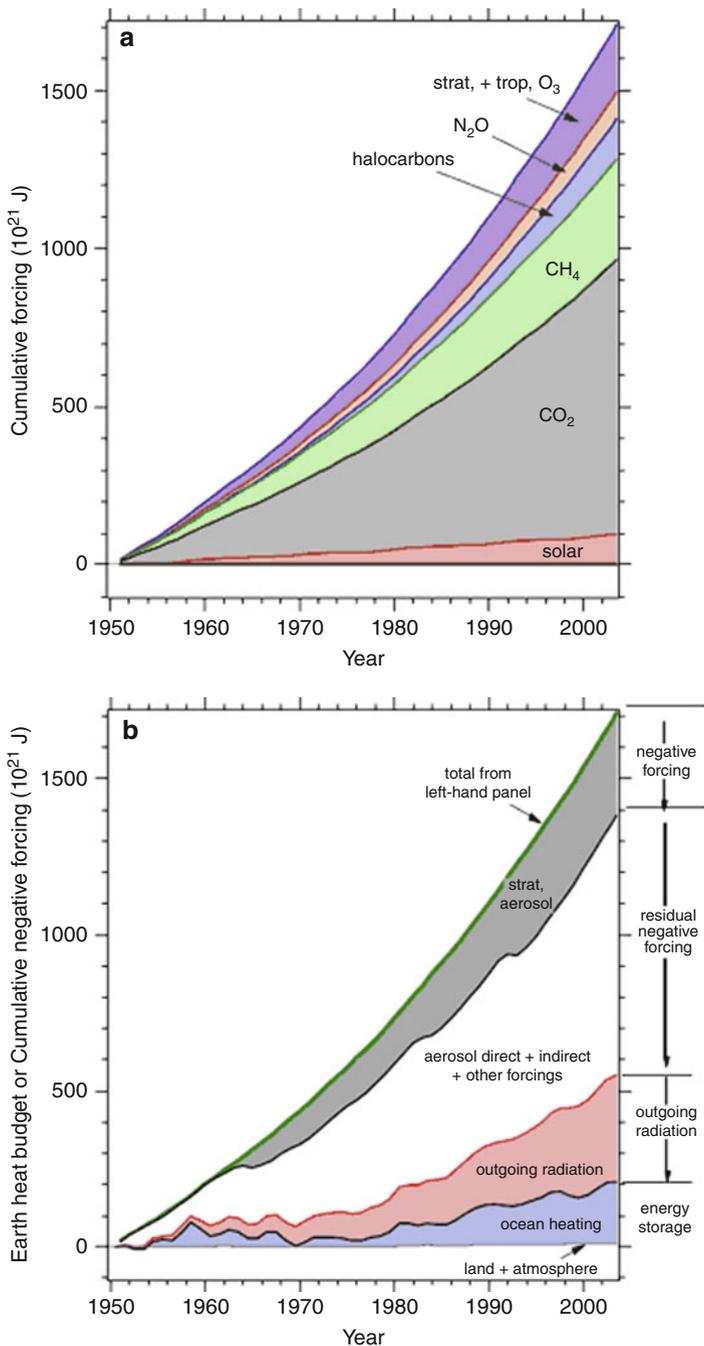


Fig. 5.16 (a) Cumulative energy budget for the Earth since 1950, showing mostly positive and mostly long-lived forcing agents from 1950 through 2004 (From Murphy et al. 2009). (b) Cumulative negative forcings such as stratospheric aerosols, direct and indirect aerosol forcing, increased outgoing radiation from a warming Earth, and the amount remaining to heat the Earth (From Murphy et al. 2009)

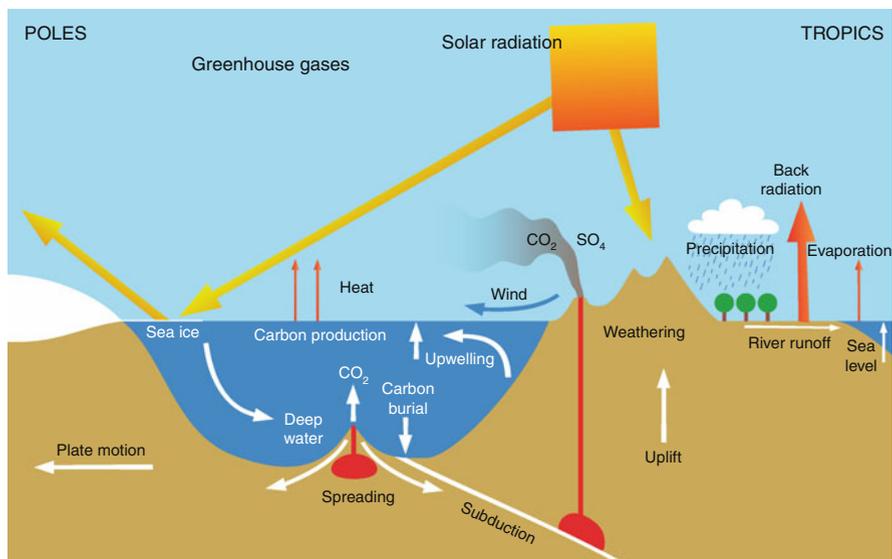


Fig. 5.17 The major components of the climate system. H₂O_v is water vapor (Source: John Cook Redrawn from Ruddiman 2001)

Feedbacks are either positive or negative. A positive feedback continues a forcing direction. If the climate is warming and a part of the climate system causes additional warming, the feedback is positive as in the case of the melting ice. If the climate is warming and a part of the climate system slows, stops, or reverses the warming, the feedback is negative. If glaciers begin to grow again and sea ice expands and more sunlight is reflected back to space and the Earth cools, the feedback is negative.

Energy from Earth's interior (either generated by radioactive decay or remnant heat from the Earth's early molten state) reaches the surface from volcanic activity on the sea floor and on land. This is the energy that causes volcanoes to form and drives the Earth's crustal plates and it is this energy that causes the plates to move and continents to drift.

Energy from the Sun retained by Earth's atmosphere is distributed throughout the Earth system; it has been described as a "cascade" of energy throughout the system. This energy results in plants producing oxygen, sugars, water, and more plant material by photosynthesis as plants grow.

5.20 Climate Sensitivity

Climate sensitivity is usually expressed as the Earth's temperature that would be expected as a result of a doubling of CO₂ but we know that climate is sensitive to more things than just CO₂, such as all forcings. The IPCC AR4 2007 defines

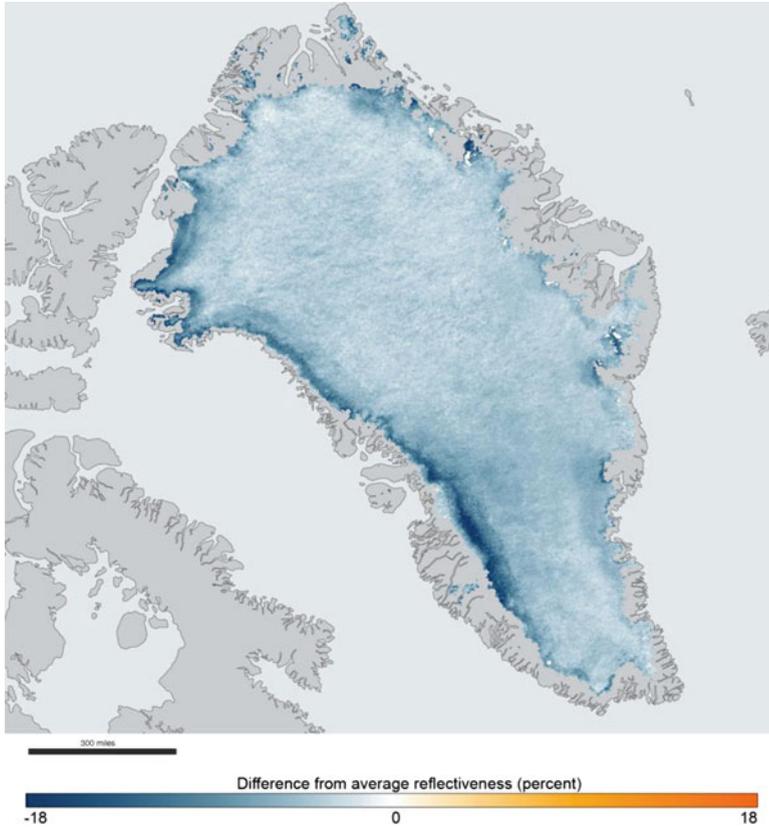


Fig. 5.18 The difference between the amounts of sunlight Greenland reflects in the summer of 2011 versus the average percent it reflected between 2000 and 2006. Virtually the entire ice sheet shows some change, with some areas reflecting close to 20% less light than a decade ago. The map is based on observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on NASA’s Terra and Aqua satellites (NASA, Public Domain)

climate sensitivity as follows: “The equilibrium climate sensitivity is a measure of the climate system response to sustained radiative forcing. It is defined as the equilibrium global average surface warming following a doubling of CO_2 concentration. Progress since the TAR enables an assessment that climate sensitivity is likely to be in the range of 2–4.5°C with a best estimate of about 3°C, and is very unlikely to be less than 1.5°C (Fig. 5.19). Values substantially higher than 4.5°C cannot be excluded, but agreement of models with observations is not as good for those values.”

Although we know that Earth’s climate is sensitive to forcings, the IPCC’s definition of climate sensitivity is accepted by most climate scientists.

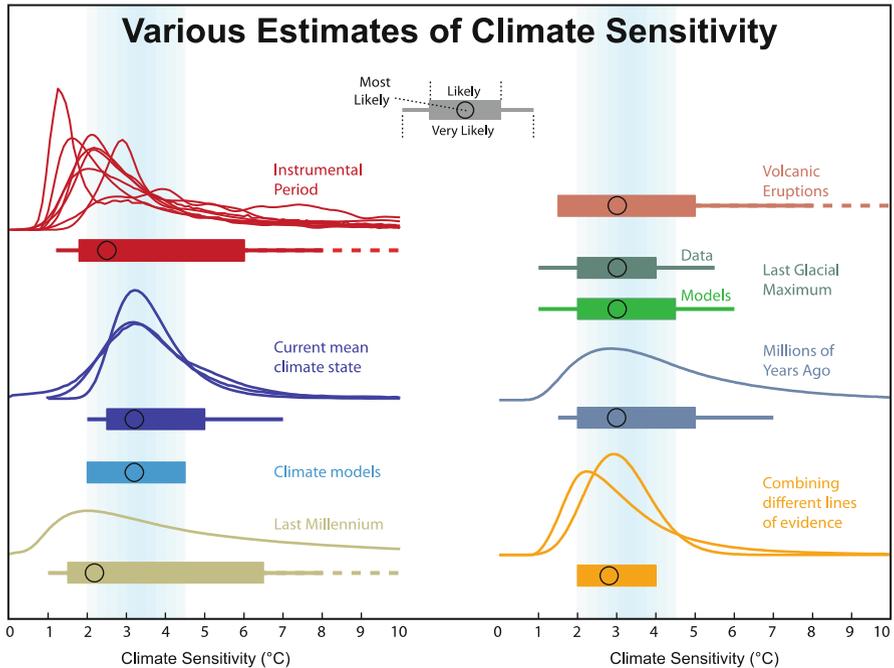


Fig. 5.19 Distributions and ranges for climate sensitivity from different lines of evidence. The circle indicates the most likely value. The thin colored bars indicate very likely value (more than 90% probability). The thicker colored bars indicate likely values (more than 66% probability). Dashed lines indicate no robust constraint on an upper bound. The IPCC likely range (2–4.5°C) and most likely value (3°C) are indicated by the vertical grey bar and black line, respectively (Adapted from Knutti and Hegerl 2008) (From SkepticalScience.com))

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