



Risks to Civilization, Humans & Planet Earth

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Introduction

Risks to civilization, humans, and planet Earth are existential risks that could threaten humankind as a whole, have adverse consequences for the course of human civilization, or even cause the end of planet Earth. The concept is expressed in various phrases such as "End of the World", "Doomsday", "Ragnarök", "Judgment Day", "Armageddon", "the Apocalypse", "Yawm al-Qiyāmah" and others.

Types of risks

Various risks exist for humanity, but not all are equal. Risks can be roughly categorized into six types based on the scope (personal, regional, global) and the intensity (endurable or terminal). The following chart provides some examples:

Typology of risk		
	Endurable	Terminal
Global	Plate tectonics	Nearby gamma-ray burst
Regional	Flash flooding	Permanent submersion
Personal	Assault	Death

Future scenarios

Many scenarios have been suggested. Some that will almost certainly end life on Earth are certain to occur, but on a very long timescale. Others are likely to happen on a shorter timescale, but will probably not completely destroy civilization. Still others are extremely unlikely, and may even be impossible. For example, Nick Bostrom writes:

Some foreseen hazards (hence not members of the current category) which have been excluded from the list on grounds that they seem too unlikely to cause a global terminal disaster are: solar flares, supernovae, black hole explosions or mergers, gamma-ray bursts, galactic center outbursts, buildup of air pollution, gradual loss of human fertility, and various religious doomsday scenarios.

Humanity

Some threats for humanity come from humanity itself.

Warfare and mass destruction

The scenarios that have been explored most frequently are nuclear warfare and a Doomsday device. It is difficult to predict whether it would exterminate humanity, but very certainly could alter civilization in the event of a nuclear winter.

Artificial intelligence

Another category of disasters are unforeseen consequences of technology.

It has been suggested that learning computers that rapidly become superintelligent may take unforeseen actions or that robots would out-compete humanity. Because of its exceptional scheduling and organizational capability and the range of novel technologies it could develop, it is possible that the first Earth superintelligence to emerge could rapidly become matchless and unrivaled: conceivably it would be able to bring about almost any possible outcome, and be able to foil virtually any attempt that threatened to prevent it achieving its desires. It could eliminate, wiping out if it chose, any other challenging rival intellects; alternatively it might manipulate or persuade them to change their behavior towards its own interests, or it may merely obstruct their attempts at interference.

Vernor Vinge has suggested that a moment may come when computers and robots are smarter than humans. He calls this "the Singularity." He suggests that it may be somewhat or possibly very dangerous for humans. This is discussed by a philosophy called Singularitarianism.

In 2009, experts attended a conference hosted by the Association for the Advancement of Artificial Intelligence (AAAI) to discuss whether computers and robots might be able to acquire any sort of autonomy, and how much these abilities might pose a threat or hazard. They noted that some robots have acquired various forms of semi-autonomy, including being able to find power sources on their own and being able to independently choose targets to attack with weapons. They also noted that some computer viruses can evade elimination and have achieved "cockroach intelligence." They noted that self-awareness as depicted in science-fiction is probably unlikely, but that there were other potential hazards and pitfalls. Various media sources and scientific groups have noted separate trends in differing areas which might together result in greater robotic functionalities and autonomy, and which pose some inherent concerns.

Some experts and academics have questioned the use of robots for military combat, especially when such robots are given some degree of autonomous functions. There are also concerns about technology which might allow some armed robots to be controlled mainly by other robots. The US Navy has funded a report which indicates that as military robots become more complex, there should be greater attention to implications of their ability to make autonomous decisions. One researcher states that autonomous robots might be more humane, as they could make decisions more effectively. However, other experts question this.

Biotechnology could lead to the creation of a pandemic, Nanotechnology could lead to grey goo in which out-of-control self-replicating robots consume all living matter on Earth while building more of themselves - in both cases, either deliberately or by accident. It has also been suggested that physical scientists might accidentally create a device that could destroy the earth and the solar system.

Climate change and ecology

It has been suggested that runaway global warming might cause the climate on Earth to become like Venus, which would make it uninhabitable. In less extreme scenarios it could cause the end of civilization, as we know it. According to a UN climate report, the Himalayan glaciers that are the sources of Asia's biggest rivers - Ganges, Indus, Brahmaputra, Yangtze, Mekong, Salween and Yellow - could disappear by 2350 as temperatures rise, although an initial announcement of that report erroneously stated the date as 2035. Approximately 3 billion people live in the drainage basin of the Himalayan rivers, which is almost half of the current human population.

The Himalayan system, which includes outlying subranges, stretches across: Afghanistan, Bangladesh, Bhutan, People's Republic of China, India, Nepal, Burma, Cambodia, Thailand, Laos, Vietnam, Malaysia and Pakistan. Some of the world's major rivers, Ganges, Indus, Brahmaputra, Yangtze, Mekong, Salween and Yellow River, rise in the Himalayas, and their combined drainage basin in India, China, Pakistan, Bangladesh, Nepal and Myanmar could experience floods followed by droughts in coming decades. In India alone, the Ganges provides water for drinking and farming for more than 500 million people. The west coast of North America, which gets much of its water from glaciers in mountain ranges such as the Rocky Mountains, Cascade Mountains and Sierra Nevada, also would be affected. According to the California Department of Water Resources, if more water supplies are not found by 2020, California residents will face a water shortfall nearly as great as the amount consumed today.

Directly linked to observed increases in the intensity and frequency of natural disasters, global warming and climate change are now considered key drivers behind rising global humanitarian and emergency relief needs. According to the UN's Office for the Coordination of Humanitarian Affairs (OCHA), climate disasters are on the rise. Around 70 percent of disasters are now climate related – up from around 50 percent from two decades ago. These disasters take a heavier human toll and come with a higher price tag. In the last decade, 2.4 billion people were affected by climate related disasters, compared to 1.7 billion in the previous decade and the cost of responding to disasters has risen tenfold between 1992 and 2008. Destructive sudden heavy rains, intense tropical storms, repeated flooding and droughts are likely to increase, as will the vulnerability of local communities in the absence of strong concerted action.

Approximately 40% of the world's agricultural land is seriously degraded. In Africa, if current trends of soil degradation continue, the continent might be able to feed just 25% of its population by 2025, according to UNU's Ghana-based Institute for Natural Resources in Africa.

James Lovelock, creator of the Gaia hypothesis, in his book *The Revenge of Gaia* (2006), has suggested that the elimination of rain forests, and the falling planetary biodiversity is removing the homeostatic negative feedback mechanisms that maintain climate stability by reducing the effects of greenhouse gas emissions (particularly carbon dioxide). With the heating of the oceans, the extension of the thermocline layer into Arctic and Antarctic waters is preventing the overturning and nutrient enrichment necessary for algal blooms of phytoplankton on which the ecosystems of these areas depend. With the loss of phytoplankton and tropical rain forests, two of the main carbon dioxide sinks for reducing global warming, he suggests a runaway positive feedback effect could cause tropical deserts to cover most of the world's tropical regions, and the disappearance of polar ice caps, posing a serious challenge to global civilization.

Using scenario analysis, the Global Scenario Group (GSG), a coalition of international scientists convened by Paul Raskin, developed a series of possible futures for the world as it enters a Planetary Phase of Civilization. One scenario involves the complete breakdown of civilization as the effects of climate change become more pronounced, competition for scarce resources increases, and the rift between the poor and the wealthy widens. The GSG's other scenarios, such as Policy Reform, Eco-Communalism, and Great Transition avoid this societal collapse and eventually result in environmental and social sustainability. They claim the outcome is dependent on human choice and the possible formation of a global citizens movement which could influence the trajectory of global development.

Global pandemic

A less predictable scenario is a global pandemic. For example, if HIV were to mutate and become as transmissible as the common cold, the consequences would be disastrous. It has been hypothesised that such an extremely virulent pathogen might not evolve. This is because a pathogen that quickly kills its hosts might not have enough time to spread to new ones, while one that kills its hosts more slowly or not at all will allow carriers more time to spread the infection, and thus likely out-compete a more lethal species or strain. This simple model predicts that if virulence and transmission are not linked in any way, pathogens will evolve towards low virulence and rapid transmission. However, this assumption is not always valid and in more complex models, where the level of virulence and the rate of transmission are related, high levels of virulence can evolve. The level of virulence that is possible is instead limited by the existence of complex populations of hosts, with different susceptibilities to infection, or by some hosts being geographically isolated. The size of the host population and competition between different strains of pathogens can also alter virulence. Interestingly, a pathogen that only infects humans as a secondary host and usually infects another species (a zoonosis) may have little constraint on its virulence in people, since infection here is an accidental event and its evolution is driven by events in another species.

Climate change and global warming

Climate change is any long-term significant change in the expected patterns of average weather of a specific region (or, more relevantly to contemporary socio-political concerns, of the Earth as a whole) over an appropriately significant period of time. Climate change reflects abnormal variations to the expected climate within the Earth's atmosphere and subsequent effects on other parts of the Earth, such as in the ice caps over durations ranging from decades to millions of years. According to the UN's Office for the Coordination of Humanitarian Affairs (OCHA), climate disasters are on the rise. Around 70 percent of disasters are now climate related – up from around 50 percent from two decades ago. These disasters take a heavier human toll and come with a higher price tag. In the last decade, 2.4 billion people were affected by climate related disasters, compared to 1.7 billion in the previous decade and the cost of responding to disasters has risen tenfold between 1992 and 2008. Destructive sudden heavy rains, intense tropical storms, repeated flooding and droughts are likely to increase, as will the vulnerability of local communities in the absence of strong concerted action. Sea level rise may completely inundate certain areas.

Ice age

In the history of the Earth, twelve ice ages have occurred. More ice ages will be possible at an interval of 40,000–100,000 years although engineers working for Posiva, a Finnish company involved in the underground storage of nuclear waste, have built their facility to withstand an Ice Age starting as 'soon' as 20,000 years. An Ice Age would have a serious impact on civilization because vast areas of land (mainly in North America, Europe, and Asia) could become uninhabitable. It would still be possible to live in the tropical regions, but with possible loss of humidity/water. Currently, the world is existing in an interglacial period within a much older glacial event. The last glacial expansion ended about 10,000 years ago, and all civilizations evolved later.

Ecological disaster

An ecological disaster, such as world crop failure and collapse of ecosystem services, could be induced by the present trends of overpopulation, economic development, and non-sustainable agriculture. Most of these scenarios involve one or more of the following: Holocene extinction event, scarcity of water that could lead to approximately one half of the Earth's population being without safe drinking water, pollinator decline, overfishing, massive deforestation, desertification, climate change, or massive water pollution episodes. A very recent threat in this direction is colony collapse disorder, a phenomenon that might foreshadow the imminent extinction of the Western honeybee. As the bee plays a vital role in pollination, its extinction would severely disrupt the food chain.

World population and agricultural crisis

The 20th century saw a rapid increase in human population due to medical developments and massive increase in agricultural productivity made by the Green Revolution. Between

1950 and 1984, as the Green Revolution transformed agriculture around the globe, world grain production increased by 250%. The Green Revolution in agriculture helped food production to keep pace with worldwide population growth or actually enabled population growth. The energy for the Green Revolution was provided by fossil fuels in the form of fertilizers (natural gas), pesticides (oil), and hydrocarbon fueled irrigation. David Pimentel, professor of ecology and agriculture at Cornell University, and Mario Giampietro, senior researcher at the National Research Institute on Food and Nutrition (INRAN), place in their study *Food, Land, Population and the U.S. Economy* the maximum U.S. population for a sustainable economy at 200 million. To achieve a sustainable economy and avert disaster, the United States must reduce its population by at least one-third, and world population will have to be reduced by two-thirds, says the study.

The authors of this study believe that the mentioned agricultural crisis will only begin to impact us after 2020, and will not become critical until 2050. Geologist Dale Allen Pfeiffer claims that coming decades could see spiraling food prices without relief and massive starvation on a global level such as never experienced before.

Wheat is humanity's 3rd most produced cereal. Extant fungal infections such as Ug99 (a kind of stem rust) can cause 100% crop losses in most modern varieties. Little or no treatment is possible and infection spreads on the wind. Should the world's large grain producing areas become infected then there would be a crisis in wheat availability leading to price spikes and shortages in other food stuffs.

Supervolcano

When the supervolcano at Yellowstone last erupted 640,000 years ago, the magma and ash ejected from the caldera covered most of the United States west of the Mississippi river and part of northeastern Mexico. Another such eruption could threaten civilization. Such an eruption could also release large amounts of gases that could alter the balance of the planet's carbon dioxide and cause a runaway greenhouse effect, or enough pyroclastic debris and other material might be thrown into the atmosphere to partially block out the sun and cause a volcanic winter, as happened in 1816 following the eruption of Mount Tambora, the so-called Year Without a Summer. Such an eruption might cause the immediate deaths of millions of people several hundred miles from the eruption, and perhaps billions of deaths worldwide due to the failure of the monsoon, as well as destruction of the "American breadbasket", causing starvation on a massive scale. Supervolcanoes are more likely threats than many others, as a prehistoric Indonesian supervolcano eruption may have reduced the human population to only a few thousand individuals, while no catastrophic bolide impact, for example, has occurred since long before modern humans evolved.

Megatsunami

Another possibility is a megatsunami. A megatsunami could, for example, destroy the entire East Coast of the United States. The coastal areas of the entire world could also be

flooded in case of the collapse of the West Antarctic Ice Sheet. While none of these scenarios are likely to destroy humanity completely, they could regionally threaten civilization. There have been two recent high-fatality tsunamis--after the 2011 Tōhoku earthquake and the 2004 Indian Ocean earthquake, although they were not large enough to be considered megatsunamis. A megatsunami could have astronomical origins as well, such as an asteroid impact in an ocean.

Distant future

There are a number of cosmological theories as to the universe's ultimate fate that exclude the indefinite continuation of life. Most involve time periods and distant futures much greater than the current 13.7-billion-year age of the universe. A long-established and widely accepted theory is the eventual heat death of the universe.

Calculations indicate that the Andromeda Galaxy is on a collision course with the Milky Way. Andromeda is approaching at an average speed of about 140 kilometres (87 miles) per second and thus impact is predicted in about 3 billion years. This merging could eject the solar system in a more eccentric orbit and an unwanted position in the merged galaxy causing our planet to become uninhabitable, even if an actual collision does not take place.

The theory of stellar evolution predicts that our Sun will exhaust its hydrogen core and become a red giant in about 5 billion years, becoming thousands of times more luminous and losing roughly 30% of its current mass. Ignoring tidal effects, the Earth would then orbit 1.7 AU (250,000,000 km) from the Sun at its maximum radius. This would allow the Earth to escape being enveloped by the Sun's now expanded and thin outer atmosphere, though most life, if not all, would perish due to the Sun's proximity. However, a more recent study suggests that the Earth's orbit will decay due to the effects of tidal drag, causing it to enter the Sun's expanded atmosphere and be destroyed in 7.6 billion years. Before being swallowed by the Sun, the Earth's oceans would evaporate, and the Earth would finally be destroyed by tidal forces. However, this fate is not inevitable - it appears possible to move the Earth to a more distant orbit, using repeated close encounters with asteroids.

Meteorite impact

Earth has collided with several large asteroids in recent geological history. The Cretaceous-Tertiary asteroid, for example, is theorized to have caused the extinction of the dinosaurs 65 million years ago. If such an object struck Earth it could have a serious impact on civilization. It is even possible that humanity would be completely destroyed; for this to occur the asteroid would need to be at least 1 km (0.62 miles) in diameter, but probably between 3 and 10 km (2–6 miles). Asteroids with a 1 km diameter have impacted the Earth on average once every 500,000 years. Larger asteroids are less common. So-called Near-Earth asteroids are regularly being observed.

1.4 million years from now the star Gliese 710 is expected to cause an increase in the number of meteoroids in the vicinity of Earth by passing within 1.1 light years of the Sun. Some models predict that this will cause a large number of comets from the Oort cloud to impact Earth, whereas other models predict only a 5% increase in the rate of impact.

Other cosmic threats

A number of other scenarios have been suggested. Massive objects, e.g., a star, large planet or black hole, could be catastrophic if a close encounter occurred in the solar system. (Gravity from the wandering objects might disrupt orbits and/or fling bodies into other objects, thus resulting in meteorite impacts or climate change. Also, heat from the wandering objects might cause extinctions; tidal forces could cause erosion along our coastlines.) Another threat might come from gamma ray bursts. Both are very unlikely.

Still others see extraterrestrial life as a possible threat to humankind; although alien life has never been found, scientists such as Carl Sagan have postulated that the existence of extraterrestrial life is very likely. In 1969, the "Extra-Terrestrial Exposure Law" was added to the Code of Federal Regulations (Title 14, Section 1211) in response to the possibility of biological contamination resulting from the US Apollo Space Program. It was removed in 1991. Scientists consider such a scenario technically possible, but unlikely.

In April 2008, it was announced that two simulations of long-term planetary movement, one at Paris Observatory and the other at University of California, Santa Cruz indicate a 1% chance that Mercury's orbit could be made unstable by Jupiter's gravitational pull sometime during the lifespan of the sun. Were this to happen, the simulations suggest a collision with Earth could be one of four possible outcomes (the others being Mercury colliding with the Sun, colliding with Venus, or being ejected from the solar system altogether). If Mercury were to collide with the Earth, all life on Earth would be obliterated and the impact might displace enough matter into orbit to form another moon. Note that an asteroid just 15 km wide is said to have caused the extinction of the dinosaurs; Mercury is some 5,000 km in diameter.

Other scenarios

- **Peak oil:** Fossil fuels attain a level of scarcity before an economically viable replacement is devised, leading firstly to economic strain, followed by the collapse of modern agriculture, then to mass starvation.
- **Antibiotic resistance:** Natural selection would create super bacteria that are resistant to antibiotics, devastating the world population and causing a global collapse of civilization.
- **Gulf Stream shutdown:** There is some speculation that global warming could, via a shutdown or slowdown of the thermohaline circulation, trigger localized cooling in the North Atlantic and lead to cooling in that region. This would affect in particular areas like Ireland, the Nordic countries, and Britain that are warmed by the North Atlantic drift.

- Mutual assured destruction: A full scale nuclear war could kill billions, and the resulting nuclear winter would effectively crush any form of civilization.
- Overpopulation: Some scenarios of simultaneous ecological (food & water production) and economical collapses with overpopulation are presumed to lead to a global civil war, where the remaining habitable areas are destroyed by competing humans (so called 'Mad Max'-scenario).
- Famine: As of late 2007, increased farming for use in biofuels, along with world oil prices spiking to more than \$140 per barrel, had pushed up the price of grain used to feed poultry and dairy cows and other cattle, causing higher prices of wheat (up 58%), soybean (up 32%), and maize (up 11%) over the year. Food riots have recently taken place in many countries across the world. An epidemic of stem rust on wheat caused by race Ug99 is currently spreading across Africa and into Asia and is causing major concern. Scientists say millions of people face starvation.
- Experimental accident: Investigations in nuclear and high energy physics could conceivably create unusual conditions with catastrophic consequences. For example, scientists worried that the first nuclear test might ignite the atmosphere. More recently, others worried that the RHIC or the Large Hadron Collider might start a chain-reaction global disaster involving black holes or false vacuum states. These particular concerns have been refuted,, but the general concern remains.
- Dysgenics: Widespread occurrence of defective or disadvantageous human genes could cause a catastrophic decline in the quality of human life, or its total cessation.
- Hypercane
- Economic collapse
- Mass extinction
- Overconsumption
- Colony collapse disorder

Historical fictional scenarios

Sir Isaac Newton (1642–1727) studied old texts and surmised that the end of the world would happen no earlier than 2060, although he was reluctant to put an exact date on it.

The belief that the Mayan civilization's Long Count calendar ends abruptly on December 21, 2012, is a misconception due to the Mayan practice of using only five places in Long Count Calendar inscriptions. On some monuments the Mayan calculated dates far into the past and future but there is no end of the world date. There will be a Piktun ending (a cycle of 13 144,000 day Bak'tuns) on December 21, 2012. A Piktun marks the end of a 1,872,000 day or approximately 5125 year period and is a significant event in the Mayan calendar. However, there is no historical or scientific evidence that the Mayas believed it would be a doomsday. Some believe it will just be the beginning of another Piktun.

The cataclysmic pole shift hypothesis was formulated in 1872. Revisited repeatedly in the second half of the 20th century, it proposes that the axis of the Earth with respect to the

crust could change extremely rapidly, causing massive earthquakes, tsunamis, and damaging local climate changes. The hypothesis is contradicted by the mainstream scientific interpretation of geological data, which indicates that true polar wander does occur, but very slowly over millions of years.

Chapter-1

Impact Event



Artist's impression of a major impact event. The collision between Earth and an asteroid a few kilometers in diameter may release as much energy as several million nuclear weapons detonating simultaneously.

An **impact event** is the collision of a large meteorite, asteroid, comet, or other celestial object with the Earth or another planet. Throughout recorded history, hundreds of minor impact events (and exploding bolides) have been reported, with some occurrences causing deaths, injuries, property damage or other significant localised consequences. An impact event in an ocean or sea may create a tsunami (a giant wave), which can cause destruction both at sea and on land near a seashore.

The latest major impact event occurred in Kaali, Estonia about 700 BC.

Impact events have been a plot and background element in science fiction since knowledge of real impacts became established in the scientific mainstream.

Sizes and frequencies



Something undergoing atmospheric entry

Small objects frequently collide with the Earth. There is an inverse relationship between the size of the object and the frequency that such objects hit the earth. Asteroids with a 1 km (0.62 mi) diameter strike the Earth every 500,000 years on average. Large collisions – with 5 km (3 mi) objects – happen approximately once every ten million years. The last known impact of an object of 10 km (6 mi) or more in diameter was at the Cretaceous-Tertiary extinction event 65 million years ago.

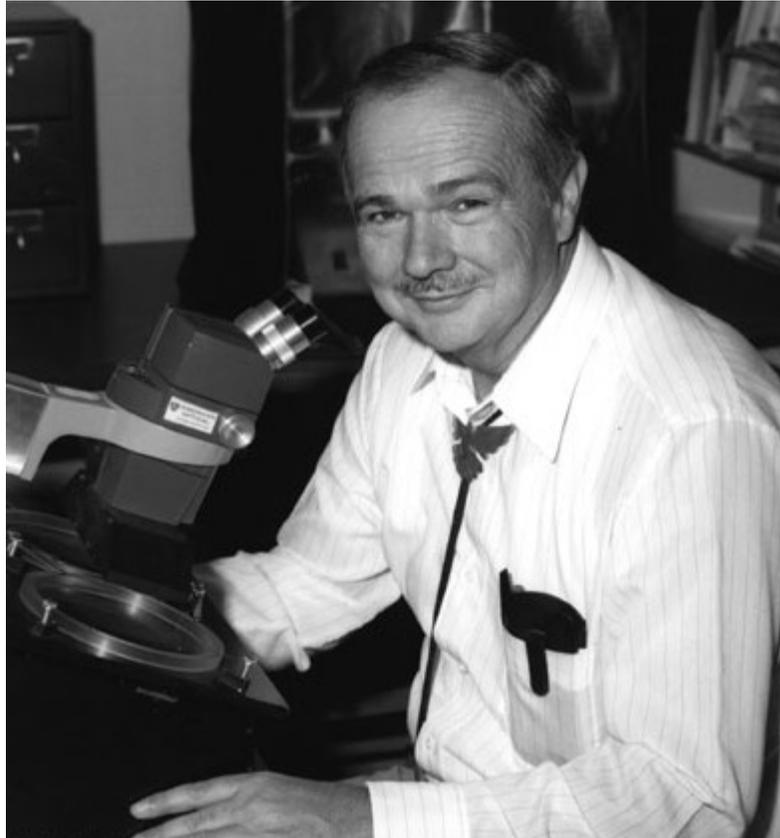
Asteroids with diameters of 5 to 10 m (16 to 33 ft) enter the Earth's atmosphere approximately once per year, with as much energy as Little Boy, the atomic bomb dropped on Hiroshima, approximately 15 kilotonnes of TNT. These ordinarily explode in the upper atmosphere, and most or all of the solids are vaporized. Objects with diameters over 50 m (164 ft) strike the Earth approximately once every thousand years, producing explosions comparable to the one known to have detonated above Tunguska in 1908. At least one known asteroid with a diameter of over 1 km (0.62 mi), (29075) 1950 DA, has a possibility of colliding with Earth on March 16, 2880, with a Torino Scale rating of two.

Objects with diameters smaller than 10 m (33 ft) are called meteoroids (or meteorites if they strike the ground). An estimated 500 meteorites reach the surface each year, but only 5 or 6 of these are typically recovered and made known to scientists.

Geology of Earth-impact events

Earth has gone through periods of abrupt and catastrophic change, some due to the impact of large asteroids and comets on the planet. A few of these impacts may have caused massive climate change and the extinction of large numbers of plant and animal species.

The Moon is widely attributed to a huge impact early in Earth's history. Impact events earlier in the history of Earth have been credited with creative as well as destructive events; it has been proposed that the water in the Earth's oceans was delivered by impacting comets, and some have suggested that the origins of life may have been influenced by impacting objects by bringing organic chemicals or lifeforms to the Earth's surface, a theory known as exogenesis.



Eugene Merle Shoemaker was first to prove that meteor impacts have affected the Earth.

These modified views of the Earth's history did not emerge until relatively recently, chiefly due to a lack of direct observations and the difficulty in recognizing the signs of an Earth impact because of erosion and weathering. Large-scale terrestrial impacts of the sort that produced the Barringer Crater, locally known as Meteor Crater, northeast of Flagstaff, Arizona, are rare. Instead, it was widely thought that cratering was the result of volcanism: the Barringer Crater, for example, was ascribed to a prehistoric volcanic explosion (not an unreasonable hypothesis, given that the volcanic San Francisco Peaks stand only 30 miles (48 km) to the west). Similarly, the craters on the surface of the Moon were ascribed to volcanism.

It was not until 1903–1905 that the Barringer Crater was correctly identified as being an impact crater, and it was not until as recently as 1963 that research by Eugene Merle Shoemaker conclusively proved this hypothesis. The findings of late 20th-century space

exploration and the work of scientists such as Shoemaker demonstrated that impact cratering was by far the most widespread geological process at work on the solar system's solid bodies. Every surveyed solid body in the solar system was found to be cratered, there was no reason to believe that the Earth had somehow escaped bombardment from space. The first observation of a major impact event occurred in 1994: the collision of the comet Shoemaker-Levy 9 with Jupiter; to date, no such events have been observed on Earth.

Based on crater formation rates determined from the Earth's closest celestial partner, the Moon, astrogeologists have determined that during the last 600 million years, the Earth has been struck by 60 objects of a diameter of 5 km (3 mi) or more. The smallest of these impactors would release the equivalent of ten million megatons of TNT and leave a crater 95 km (60 mi) across. For comparison, the largest nuclear weapon ever detonated, the Tsar Bomba, had a yield of 50 megatons.

Recent prehistoric impact events

In addition to the extremely large impacts that happen every few tens of millions of years, there are many smaller impacts that occur more frequently but which leave correspondingly smaller traces behind. Due to the strong forces of erosion at work on Earth, only relatively recent examples of these smaller impacts are known. A few of the more famous or interesting examples are:



Aerial view of Barringer Crater in Arizona

- Barringer Crater in the USA, the first crater to be proven the result of an impact, ~50,000 years old.
- the Rio Cuarto craters in Argentina, produced by an asteroid striking Earth at a very low angle, ~10,000 years old.
- the Lonar crater lake in Asia, which now has a flourishing semi-tropical jungle around it, ~52,000 years old (though a study published in 2010 gives a much greater age).
- the Henbury craters in Australia (~5,000 years old), and Kaali craters in Estonia (~2700 years old), apparently produced by objects which broke up before impact.

The Clovis comet hypothesis is a theory that an air burst from a large comet above or even into the Laurentide Ice Sheet north of the Great Lakes set all of the North American continent ablaze around 12,900 years ago. The theory attempts to explain the extinction of most of the large animals in North America and the demise of the North American stone age Clovis culture about at the end of the Pleistocene epoch. Proponents claim the existence of a mysterious charred carbon-rich layer of soil found at some 50 Clovis-age sites across the continent. It has been criticized for not being consistent with paleoindian population estimates.

More recent prehistoric impacts are theorized by the Holocene Impact Working Group, including Dallas Abbott of Columbia University's Lamont-Doherty Earth Observatory in Palisades, N.Y. This group points to four enormous chevron sediment deposits at the southern end of Madagascar, containing deep-ocean microfossils fused with metals typically formed by cosmic impacts. All of the chevrons point toward a spot in the middle of the Indian Ocean where newly discovered Burckle crater, 29 km (18 mi) in diameter, or about 25 times larger than Barringer Crater, lies 3,800 m (12,500 ft) below the surface. This group posits that a large asteroid or comet impact c. 2800-3000 BC produced a mega-tsunami at least 180 m (590 ft) high, a catastrophic event that would have affected humanity's cradles of civilization. If this and other recent impacts prove correct, the rate of asteroid impacts is much higher than currently thought.

Years 533–534 CE \pm 2 impact events have been proposed by the dendrochronologist Mike Baillie as a possible cause of several brief (typically 5-10 year) climatic downturns recorded in ancient tree ring patterns. In his book *Exodus to King Arthur: Catastrophic Encounters with Comets*, he highlights four such events and suggests that these might have been caused by the dust veils thrown up by the impact of cometary debris.

Modern impact events

A Chinese record states that 10,000 people were killed in Shanxi Province in 1490 by a hail of "falling stones"; some astronomers surmise that this may describe the breakup of a large asteroid, although they find the number of deaths implausible.

Kamil Crater, discovered from **Google Earth** image review in Egypt, 45 meters in diameter, 10 meters deep is thought to have been formed less than 3,500 years ago in a

then-unpopulated region of Western Egypt. It was found February 19, 2009 by V. de Michelle on a Google Earth image of the East Uweinat Desert, Egypt.

The Mahuika crater may have resulted from a modern impact event. The crater is located south of the Snares Islands (120 km (70 mi) southwest of Stewart Island) on the southern New Zealand shelf and is approximately 20 kilometres (12 mi) wide. Material extracted from Siple Dome ice core melt water indicates that the impact occurred around 1443 A.D.

The Wabar craters in Arabia may have been created sometime during the past few hundred years.



Trees knocked over by the Tunguska blast

The most significant recorded impact in recent times was the Tunguska event, which occurred in Siberia, Russia, in 1908. This incident involved an explosion that was probably caused by the airburst of an asteroid or comet 5 to 10 km (3.1 to 6.2 mi) above the Earth's surface, felling an estimated 80 million trees over 2,150 km² (830 sq mi).

The late Eugene Shoemaker of the U.S. Geological Survey came up with an estimate of the rate of Earth impacts, and suggested that an event about the size of the nuclear weapon that destroyed Hiroshima occurs about once a year. Such events would seem to be spectacularly obvious, but they generally go unnoticed for a number of reasons: the majority of the Earth's surface is covered by water; a good portion of the land surface is uninhabited; and the explosions generally occur at relatively high altitude, resulting in a

huge flash and thunderclap but no real damage. Some have been observed. Noteworthy examples include the Sikhote-Alin Meteorite fall in Primorye, far eastern Russia, in 1947, and the Revelstoke fireball of 1965, which occurred over the snows of British Columbia, Canada.

A small number of meteorite falls have been observed with automated cameras and recovered following calculation of the impact point. The first of these was the Pribram meteorite, which fell in Czechoslovakia (now the Czech Republic) in 1959. In this case, two cameras used to photograph meteors captured images of the fireball. The images were used both to determine the location of the stones on the ground and, more significantly, to calculate for the first time an accurate orbit for a recovered meteorite.

Following the Pribram fall, other nations established automated observing programs aimed at studying infalling meteorites. One of these was the *Prairie Network*, operated by the Smithsonian Astrophysical Observatory from 1963 to 1975 in the midwestern US. This program also observed a meteorite fall, the *Lost City* chondrite, allowing its recovery and a calculation of its orbit. Another program in Canada, the Meteorite Observation and Recovery Project, ran from 1971 to 1985. It too recovered a single meteorite, *Innisfree*, in 1977. Finally, observations by the European Fireball Network, a descendant of the original Czech program that recovered Pribram, led to the discovery and orbit calculations for the Neuschwanstein meteorite in 2002.

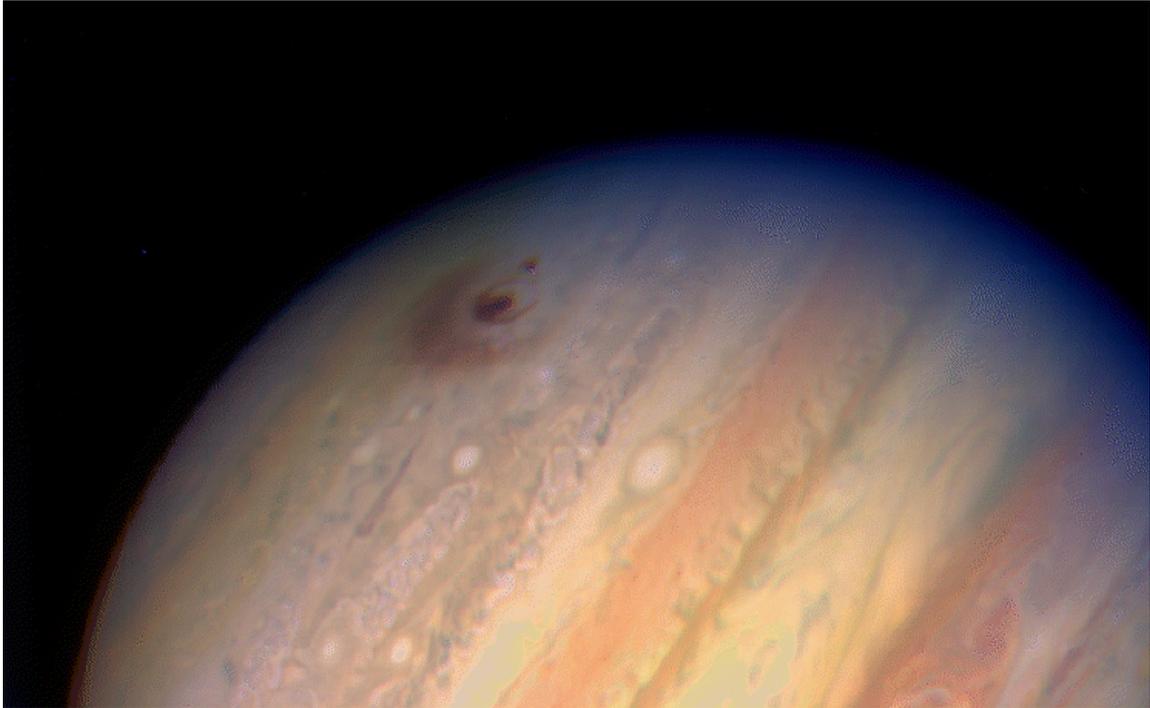
The only reported fatality from meteorite impacts is an Egyptian dog that was killed in 1911 by the Nakhla meteorite, although this report is disputed. The meteorites that struck this area were identified in the 1980s as Martian in origin.

The first known modern case of a human hit by a space rock occurred on November 30, 1954, in Sylacauga, Alabama. There a 4 kg (8.8 lb) stone chondrite crashed through a roof and hit Ann Hodges in her living room after it bounced off her radio. She was badly bruised. Several persons have since claimed to have been struck by 'meteorites' but no verifiable meteorites have resulted.

On August 10, 1972, a meteor which became known as The Great Daylight 1972 Fireball was witnessed by many people moving north over the Rocky Mountains from the U.S. Southwest to Canada. It was filmed by a tourist at the Grand Teton National Park in Wyoming with an 8-millimeter color movie camera. The object was in the range of size from a car to a house and could have ended its life in a Hiroshima-sized blast, but there was never any explosion. Analysis of the trajectory indicated that it never came much lower than 58 km (36 mi) off the ground, and the conclusion was that it had grazed Earth's atmosphere for about 100 seconds, then skipped back out of the atmosphere to return to its orbit around the Sun.

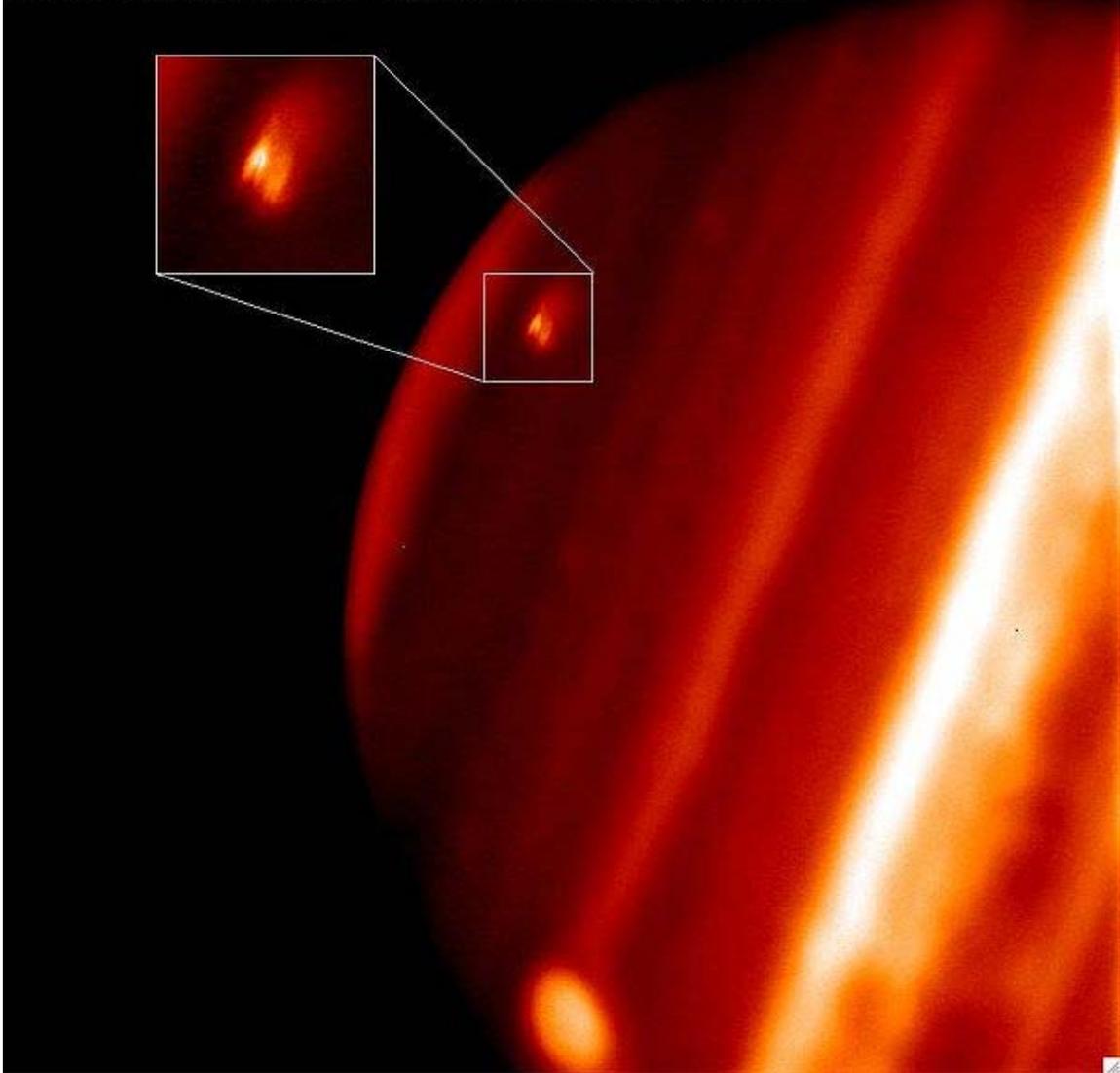
In the dark morning hours of January 18, 2000, a fireball exploded over the city of Whitehorse in the Canadian Yukon at an altitude of about 26 km (16 mi), lighting up the night like day. The meteor that produced the fireball was estimated to be about 4.6 m (15 ft) in diameter and with a weight of 180 tonnes. This blast was also featured on The

Science Channel series *Killer Asteroids*, with several witness reports from residents in Atlin, British Columbia.



Comet Shoemaker-Levy 9's scar on Jupiter (dark area near Jupiter's limb)

Keck II telescope infrared images of recent Jupiter impact



A picture of the Jupiter 2009 impact event blemish captured by the Keck II telescope and its near-infrared camera at Mauna Kea Observatory, on July 20.

A meteor was observed striking Reisadalen in Nordreisa municipality in Troms County, Norway, on June 7, 2006. Although initial witness reports stated that the resultant fireball was equivalent to the Hiroshima nuclear explosion, scientific analysis places the force of the blast at anywhere from 100-500 tonnes TNT equivalent – around 3% of Hiroshima's yield.

On September 15, 2007, a chondritic meteor crashed near the village of Carancas in southeastern Peru near Lake Titicaca, leaving a water-filled hole and spewing gases across the surrounding area. Many residents became ill, apparently from the noxious gases shortly after the impact.

On November 21, 2009, a fireball was sighted in South Africa by police and traffic cameras. The probable meteor may have landed in a remote area on the Botswana border, and likely made little impact.

Many impact events occur without being observed by anyone on the ground. Between 1975 and 1992, American missile early warning satellites picked up 136 major explosions in the upper atmosphere. In the November 21, 2002, edition of the journal *Nature*, Peter Brown of the University of Western Ontario reported on his study of U.S. early warning satellite records for the preceding 8 years. He identified 300 flashes caused by 1 to 10 m (3 to 33 ft) sized meteors in that time period and estimated the rate of Tunguska-sized events as once in 400 years. Eugene Shoemaker estimated that one of such magnitude occurs about once every 300 years, though more recent analyses have suggested he exaggerated by an order of magnitude.

The 1994 impact of Comet Shoemaker-Levy 9 with Jupiter served as a "wake-up call", and astronomers responded by starting programs such as Lincoln Near-Earth Asteroid Research (LINEAR), Near-Earth Asteroid Tracking (NEAT), Lowell Observatory Near-Earth Object Search (LONEOS) and several others which have drastically increased the rate of asteroid discovery.

In 1998, two comets were observed plunging into the Sun in close succession. The first of these was on June 1 and the second the next day. A video of this, followed by a dramatic ejection of solar gas (supposedly unrelated to the impacts), can be found at the NASA website. Both of these comets evaporated before coming into contact with the surface of the Sun. According to a theory by NASA Jet Propulsion Laboratory scientist Zdeněk Sekanina, the latest impactor to actually make contact with the Sun was the "supercomet" Howard-Koomen-Michels on August 30, 1979.

On October 7, 2008, a meteoroid labeled 2008 TC3 was tracked for 20 hours as it approached Earth and as it fell through the atmosphere and impacted in Sudan. This was the first time an object was detected before it reached the atmosphere and hundreds of pieces of the meteorite were recovered from the Nubian Desert.

On July 19, 2009, a new black spot about the size of Earth was discovered in Jupiter's southern hemisphere by an amateur astronomer. Thermal infrared analysis showed it was warm and spectroscopic methods detected ammonia. JPL scientists confirmed that another impact event on Jupiter had occurred, probably a small undiscovered comet or other icy body.

Mass extinctions and impacts

In the past 540 million years there have been five generally-accepted, major mass extinctions that on average extinguished half of all species. One of the largest mass extinction to have affected life on Earth was in the Permian-Triassic, which ended the Permian period 250 million years ago and killed off 90% of all species; life on Earth took 30 million years to recover. The cause of the Permian-Triassic extinction is still matter of

debate with the age and origin of proposed impact craters, i.e. the Bedout High structure, hypothesized to be associated with it are still controversial. The last such mass extinction led to the demise of the dinosaurs and coincided with a large meteorite impact; this is the Cretaceous–Tertiary extinction event (also known as the K–T extinction event). There is no definitive evidence of impacts leading to the four other major mass extinctions.

In 1980, physicist Luis Alvarez; his son, geologist Walter Alvarez; and nuclear chemists Frank Asaro and Helen V. Michael from the University of California, Berkeley discovered unusually high concentrations of iridium in a specific layer of rock strata in the Earth's crust. Iridium is an element that is rare on Earth but relatively abundant in many meteorites. From the amount and distribution of iridium present in the 65-million-year-old "iridium layer", the Alvarez team later estimated that an asteroid of 10 to 14 km (6 to 9 mi) must have collided with the earth. This iridium layer at the K–T boundary has been found worldwide at 100 different sites. Multidirectionally shocked quartz (coesite), which is only known to form as the result of large impacts or atomic bomb explosions, has also been found in the same layer at more than 30 sites. Soot and ash at levels tens of thousands times normal levels were found with the above.

Anomalies in chromium isotopic ratios found within the K-T boundary layer strongly support the impact theory. Chromium isotopic ratios are homogeneous within the earth, therefore these isotopic anomalies exclude a volcanic origin which was also proposed as a cause for the iridium enrichment. Furthermore the chromium isotopic ratios measured in the K-T boundary are similar to the chromium isotopic ratios found in carbonaceous chondrites. Thus a probable candidate for the impactor is a carbonaceous asteroid but also a comet is possible because comets are assumed to consist of material similar to carbonaceous chondrites.

Probably the most convincing evidence for a worldwide catastrophe was the discovery of the crater which has since been named Chicxulub Crater. This crater is centered on the Yucatán Peninsula of Mexico and was discovered by Tony Camargo and Glen Pentfield while working as geophysicists for the Mexican oil company PEMEX. What they reported as a circular feature later turned out to be a crater estimated to be 180 km (110 mi) in diameter. Other researchers would later find that the end-Cretaceous extinction event that wiped out the dinosaurs had lasted for thousands of years instead of millions of years as had previously been thought. This convinced the vast majority of scientists that this extinction resulted from a point event that is most probably an extraterrestrial impact and not from increased volcanism and climate change (which would spread its main effect over a much longer time period).

Recently, several craters around the world have been dated to approximately the same age as Chicxulub — for example, the Silverpit crater in the United Kingdom, the Boltysh crater in Ukraine and the Shiva crater near India. This has led to the suggestion that the Chicxulub impact was one of several that occurred almost simultaneously, perhaps due to a disrupted comet impacting the Earth in a similar manner to the collision of Comet Shoemaker-Levy 9 with Jupiter in 1994.

It was the lack of high concentrations of iridium and shocked quartz which has prevented the acceptance of the idea that the Permian extinction was also caused by an impact. During the late Permian all the continents were combined into one supercontinent named Pangaea and all the oceans formed one superocean, Panthalassa. If an impact occurred in the ocean and not on land at all, then there would be little shocked quartz released (since oceanic crust has relatively little silica) and much less material.

Although there is now general agreement that there was a huge impact at the end of the Cretaceous that led to the iridium enrichment of the K-T boundary layer, remnants have been found of other impacts of the same order of magnitude that did not result in any mass extinctions, and there is no clear linkage between an impact and any other incident of mass extinction. Nonetheless it is now widely believed that mass extinctions due to impacts are an occasional event in the history of Earth.

Paleontologists David M. Raup and Jack Sepkoski have proposed that an extinction occurs roughly every 26 million years (though many are relatively minor). This led physicist Richard A. Muller to suggest that these extinctions could be due to a hypothetical companion star to the Sun called Nemesis periodically disrupting the orbits of comets in the Oort cloud, and leading to a large increase in the number of comets reaching the inner solar system where they might hit Earth.

Indeed, in the early history of the Earth (about four billion years ago) bolide impacts were almost certainly common since the solar system contained far more discrete bodies than at present. Such impacts could have included strikes by asteroids hundreds of kilometers in diameter, with explosions so powerful that they vaporized all the Earth's oceans. It was not until this heavy bombardment slackened that life appears to have begun to evolve on Earth.

The leading theory of the Moon's origin is the giant impact theory, which states that Earth was once hit by a planetoid the size of Mars; if this theory holds then that impact was almost certainly the largest hit Earth ever suffered.

End of civilization

An impact event is commonly seen as a scenario that would bring about the end of civilization. In 2000, *Discover Magazine* published a list of 20 possible sudden doomsday scenarios with impact event listed as the No. 1 most likely to occur. Until the 1980s this idea was not taken seriously, but all that changed after the discovery of the Chicxulub Crater which was further reinforced by witness to the Comet Shoemaker-Levy 9 event.

Chapter-2

Pandemic

A **pandemic** is an epidemic of infectious disease that is spreading through human populations across a large region; for instance multiple continents, or even worldwide. A widespread endemic disease that is stable in terms of how many people are getting sick from it is not a pandemic. Further, flu pandemics exclude seasonal flu, unless the flu of the season is a pandemic. Throughout history there have been a number of pandemics, such as smallpox and tuberculosis. More recent pandemics include the HIV pandemic and the 2009 flu pandemic.

Definition and stages

The World Health Organization (WHO) has produced a six-stage classification that describes the process by which a novel influenza virus moves from the first few infections in humans through to a pandemic. This starts with the virus mostly infecting animals, with a few cases where animals infect people, then moves through the stage where the virus begins to spread directly between people, and ends with a pandemic when infections from the new virus have spread worldwide.

A disease or condition is not a pandemic merely because it is widespread or kills many people; it must also be infectious. For instance, cancer is responsible for many deaths but is not considered a pandemic because the disease is not infectious or contagious.

In a virtual press conference in May 2009 on the influenza pandemic Dr Keiji Fukuda, Assistant Director-General ad Interim for Health Security and Environment, WHO said "An easy way to think about pandemic ... is to say: a pandemic is a global outbreak. Then you might ask yourself: "What is a global outbreak"? Global outbreak means that we see both spread of the agent ... and then we see disease activities in addition to the spread of the virus."

In planning for a possible influenza pandemic the WHO published a document on pandemic preparedness guidance in 1999, revised in 2005 and in February 2009, defining phases and appropriate actions for each phase in an aide memoir entitled *WHO pandemic phase descriptions and main actions by phase*. The 2009 revision, including definitions of a pandemic and the phases leading to its declaration, were finalized in February 2009.

The pandemic H1N1 2009 virus, was neither on the horizon at that time nor mentioned in the document.

Current pandemics

2009 influenza A/H1N1

The 2009 outbreak of a new strain of Influenza A virus subtype H1N1 created concerns that a new pandemic was occurring. In the latter half of April 2009, the World Health Organization's pandemic alert level was sequentially increased from three to five until the announcement on 11 June 2009 that the pandemic level had been raised to its highest level, level six. This was the first pandemic on this level since 1968. Dr Margaret Chan, Director-General of the World Health Organization (WHO), gave a statement on 11 June 2009 confirming that the H1N1 strain was indeed a pandemic, having nearly 30,000 confirmed cases worldwide. The alleged pandemic, and the media attention, died out starting in November, with many critics soon claiming that the WHO hyped up the dangers, providing "fear and confusion" rather than "immediate information" about the pandemic. On August 10, 2010, the WHO announced that the pandemic was over.

HIV and AIDS

HIV spread to the United States and much of the rest of the world beginning around 1969. HIV, the virus that causes AIDS, is currently a pandemic, with infection rates as high as 25% in southern and eastern Africa. In 2006 the HIV prevalence rate among pregnant women in South Africa was 29.1%. Effective education about safer sexual practices and bloodborne infection precautions training have helped to slow down infection rates in several African countries sponsoring national education programs. Infection rates are rising again in Asia and the Americas. AIDS could kill 31 million people in India and 18 million in China by 2025, according to projections by U.N. population researchers. AIDS death toll in Africa may reach 90-100 million by 2025.

Pandemics and notable epidemics through history

There have been a number of significant pandemics recorded in human history, generally zoonoses which came about with domestication of animals, such as influenza and tuberculosis. There have been a number of particularly significant epidemics that deserve mention above the "mere" destruction of cities:

- Plague of Athens, 430 BC. Typhoid fever killed a quarter of the Athenian troops, and a quarter of the population over four years. This disease fatally weakened the dominance of Athens, but the sheer virulence of the disease prevented its wider spread; i.e. it killed off its hosts at a rate faster than they could spread it. The exact cause of the plague was unknown for many years. In January 2006, researchers from the University of Athens analyzed teeth recovered from a mass grave

underneath the city, and confirmed the presence of bacteria responsible for typhoid.

- Antonine Plague, 165–180. Possibly smallpox brought to the Italian peninsula by soldiers returning from the Near East; it killed a quarter of those infected, and up to five million in all. At the height of a second outbreak, the Plague of Cyprian (251–266), which may have been the same disease, 5,000 people a day were said to be dying in Rome.
- Plague of Justinian, from 541 to 750, was the first recorded outbreak of the bubonic plague. It started in Egypt, and reached Constantinople the following spring, killing (according to the Byzantine chronicler Procopius) 10,000 a day at its height, and perhaps 40% of the city's inhabitants. The plague went on to eliminate a quarter to a half of the human population that it struck throughout the known world. It caused Europe's population to drop by around 50% between 550 and 700.
- Black Death, started 14th century. The total number of deaths worldwide is estimated at 75 million people. Eight hundred years after the last outbreak, the plague returned to Europe. Starting in Asia, the disease reached Mediterranean and western Europe in 1348 (possibly from Italian merchants fleeing fighting in the Crimea), and killed an estimated 20 to 30 million Europeans in six years; a third of the total population, and up to a half in the worst-affected urban areas. It was the first of a cycle of European plague epidemics that continued until the 18th century. During this period, more than 100 plague epidemics swept across Europe. In England, for example, epidemics would continue in two to five-year cycles from 1361 to 1480. By the 1370s, England's population was reduced by 50%. The Great Plague of London of 1665–66 was the last major outbreak of the plague in England. The disease killed approximately 100,000 people, 20% of London's population.
- Third Pandemic, started in China in the middle of the 19th century, spreading plague to all inhabited continents and killing 10 million people in India alone. During this pandemic, the United States saw its first case of plague in 1900 in San Francisco. Today, isolated cases of plague are still found in the western United States.

Encounters between European explorers and populations in the rest of the world often introduced local epidemics of extraordinary virulence. Disease killed the entire native (Guanches) population of the Canary Islands in the 16th century. Half the native population of Hispaniola in 1518 was killed by smallpox. Smallpox also ravaged Mexico in the 1520s, killing 150,000 in Tenochtitlán alone, including the emperor, and Peru in the 1530s, aiding the European conquerors. Measles killed a further two million Mexican natives in the 17th century. In 1618–1619, smallpox wiped out 90% of the Massachusetts Bay Native Americans. During the 1770s, smallpox killed at least 30% of the Pacific Northwest Native Americans. Smallpox epidemics in 1780–1782 and 1837–1838 brought devastation and drastic depopulation among the Plains Indians. Some believe that the death of up to 95% of the Native American population of the New World was caused by Old World diseases such as smallpox, measles, and influenza. Over the centuries, the

Europeans had developed high degrees of immunity to these diseases, while the indigenous peoples had no such immunity.

Smallpox devastated the native population of Australia, killing around 50% of Indigenous Australians in the early years of British colonisation. It also killed many New Zealand Māori. As late as 1848–49, as many as 40,000 out of 150,000 Hawaiians are estimated to have died of measles, whooping cough and influenza. Introduced diseases, notably smallpox, nearly wiped out the native population of Easter Island. In 1875, measles killed over 40,000 Fijians, approximately one-third of the population. The disease devastated the Andamanese population. Ainu population decreased drastically in the 19th century, due in large part to infectious diseases brought by Japanese settlers pouring into Hokkaido.

Researchers concluded that syphilis was carried from the New World to Europe after Columbus' voyages. The findings suggested Europeans could have carried the nonvenereal tropical bacteria home, where the organisms may have mutated into a more deadly form in the different conditions of Europe. The disease was more frequently fatal than it is today. Syphilis was a major killer in Europe during the Renaissance. Between 1602 and 1796, the Dutch East India Company sent almost a million Europeans to work in the Asia. Ultimately, only less than one-third made their way back to Europe. The majority died of diseases. Disease killed more British soldiers in India than war. Between 1736 and 1834 only some 10% of East India Company's officers survived to take the final voyage home.

As early as 1803, the Spanish Crown organized a mission (the Balmis expedition) to transport the smallpox vaccine to the Spanish colonies, and establish mass vaccination programs there. By 1832, the federal government of the United States established a smallpox vaccination program for Native Americans. From the beginning of the 20th century onwards, the elimination or control of disease in tropical countries became a driving force for all colonial powers. The sleeping sickness epidemic in Africa was arrested due to mobile teams systematically screening millions of people at risk. In the 20th century, the world saw the biggest increase in its population in human history due to lessening of the mortality rate in many countries due to medical advances. The world population has grown from 1.6 billion in 1900 to an estimated 6.7 billion today.

Cholera

- First cholera pandemic 1816-1826. Previously restricted to the Indian subcontinent, the pandemic began in Bengal, then spread across India by 1820. 10,000 British troops and countless Indians died during this pandemic. It extended as far as China, Indonesia (where more than 100,000 people succumbed on the island of Java alone) and the Caspian Sea before receding. Deaths in India between 1817 and 1860 are estimated to have exceeded 15 million persons. Another 23 million died between 1865 and 1917. Russian deaths during a similar period exceeded 2 million.

- Second cholera pandemic 1829–1851. Reached Russia, Hungary (about 100,000 deaths) and Germany in 1831, London in 1832 (more than 55,000 persons died in the United Kingdom), France, Canada (Ontario), and United States (New York) in the same year, and the Pacific coast of North America by 1834. A two-year outbreak began in England and Wales in 1848 and claimed 52,000 lives. It is believed that over 150,000 Americans died of cholera between 1832 and 1849.
- Third pandemic 1852–1860. Mainly affected Russia, with over a million deaths. In 1852, cholera spread east to Indonesia and later invaded China and Japan in 1854. The Philippines were infected in 1858 and Korea in 1859. In 1859, an outbreak in Bengal again led to the transmission of the disease to Iran, Iraq, Arabia and Russia.
- Fourth pandemic 1863–1875. Spread mostly in Europe and Africa. At least 30,000 of the 90,000 Mecca pilgrims fell victim to the disease. Cholera claimed 90,000 lives in Russia in 1866.
- In 1866, there was an outbreak in North America. It killed some 50,000 Americans.
- Fifth pandemic 1881-1896. The 1883-1887 epidemic cost 250,000 lives in Europe and at least 50,000 in Americas. Cholera claimed 267,890 lives in Russia (1892); 120,000 in Spain; 90,000 in Japan and 60,000 in Persia.
- In 1892, cholera contaminated the water supply of Hamburg, and caused 8606 deaths.
- Sixth pandemic 1899–1923. Had little effect in Europe because of advances in public health, but Russia was badly affected again (more than 500,000 people dying of cholera during the first quarter of the 20th century). The sixth pandemic killed more than 800,000 in India. The 1902-1904 cholera epidemic claimed over 200,000 lives in the Philippines. 27 epidemics were recorded during pilgrimages to Mecca from the 19th century to 1930, and more than 20,000 pilgrims died of cholera during the 1907–08 hajj.
- Seventh pandemic 1962-66. Began in Indonesia, called El Tor after the strain, and reached Bangladesh in 1963, India in 1964, and the USSR in 1966.

Influenza

WHO Phases	
INTER-PANDEMIC PERIOD	
1	No new influenza virus subtypes have been detected in humans. An influenza virus subtype that has caused human infection may be present in animals. If present in animals, the risk of human disease is considered to be low.
2	No new influenza virus subtypes have been detected in humans. However, a circulating animal influenza virus subtype poses a substantial risk of human disease.
PANDEMIC ALERT PERIOD	
3	Human infection(s) with a new subtype, but no human-to-human spread, or at most rare instances of spread to a close contact.
4	Small cluster(s) with limited human-to-human transmission but spread is highly localized, suggesting that the virus is not well adapted to humans.
5	Larger cluster(s) but human-to-human spread still localized, suggesting that the virus is becoming increasingly better adapted to humans, but may not yet be fully transmissible (substantial pandemic risk).
PANDEMIC PERIOD	
6	Pandemic phase: increased and sustained transmission in general population.

World Health Organization influenza pandemic alert phases

- The Greek physician Hippocrates, the "Father of Medicine", first described influenza in 412 BCE.
- The first influenza pandemic was recorded in 1580 and since then influenza pandemics occurred every 10 to 30 years.
- The "Asiatic Flu", 1889–1890, was first reported in May 1889 in Bukhara, Uzbekistan. By October, it had reached Tomsk and the Caucasus. It rapidly spread west and hit North America in December 1889, South America in February–April 1890, India in February–March 1890, and Australia in March–April 1890. It was purportedly caused by the H2N8 type of flu virus. It had a very high attack and mortality rate. About 1 million people died in this pandemic."
- The "Spanish flu", 1918–1919. First identified early in March 1918 in US troops training at Camp Funston, Kansas. By October 1918, it had spread to become a worldwide pandemic on all continents, and eventually infected about one-third of the world's population (or ≈500 million persons). Unusually deadly and virulent, it ended nearly as quickly as it began, vanishing completely within 18 months. In six months, some 50 million were dead; some estimates put the total of those killed worldwide at over twice that number. About 17 million died in India,

675,000 in the United States and 200,000 in the UK. The virus was recently reconstructed by scientists at the CDC studying remains preserved by the Alaskan permafrost. The H1N1 virus has a small, but crucial structure that that is similar to the Spanish Flu.

- The "Asian Flu", 1957–58. An H2N2 virus caused about 70,000 deaths in the United States. First identified in China in late February 1957, the Asian flu spread to the United States by June 1957. It caused about 2 million deaths globally.
- The "Hong Kong Flu", 1968–69. An H3N2 caused about 34,000 deaths in the United States. This virus was first detected in Hong Kong in early 1968, and spread to the United States later that year. This pandemic of 1968 and 1969 killed approximately one million people worldwide. Influenza A (H3N2) viruses still circulate today.

Typhus

Typhus is sometimes called "camp fever" because of its pattern of flaring up in times of strife. (It is also known as "gaol fever" and "ship fever", for its habits of spreading wildly in cramped quarters, such as jails and ships.) Emerging during the Crusades, it had its first impact in Europe in 1489, in Spain. During fighting between the Christian Spaniards and the Muslims in Granada, the Spanish lost 3,000 to war casualties, and 20,000 to typhus. In 1528, the French lost 18,000 troops in Italy, and lost supremacy in Italy to the Spanish. In 1542, 30,000 soldiers died of typhus while fighting the Ottomans in the Balkans.

During the Thirty Years' War (1618–1648), about 8 million Germans were wiped out by bubonic plague and typhus fever. The disease also played a major role in the destruction of Napoleon's *Grande Armée* in Russia in 1812. Felix Markham thinks that 450,000 soldiers crossed the Neman on 25 June 1812, of whom less than 40,000 recrossed in anything like a recognizable military formation. In early 1813 Napoleon raised a new army of 500,000 to replace his Russian losses. In the campaign of that year over 219,000 of Napoleon's soldiers were to die of typhus. Typhus played a major factor in the Irish Potato Famine. During the World War I, typhus epidemics have killed over 150,000 in Serbia. There were about 25 million infections and 3 million deaths from epidemic typhus in Russia from 1918 to 1922. Typhus also killed numerous prisoners in the Nazi concentration camps and Soviet prisoner of war camps during World War II. More than 3.5 million Soviet POWs died in the Nazi custody out of 5.7 million.

Smallpox

Smallpox is a highly contagious disease caused by the Variola virus. The disease killed an estimated 400,000 Europeans per year during the closing years of the 18th century. During the 20th century, it is estimated that smallpox was responsible for 300–500 million deaths. As recently as early 1950s an estimated 50 million cases of smallpox occurred in the world each year. After successful vaccination campaigns throughout the 19th and 20th centuries, the WHO certified the eradication of smallpox in December

1979. To this day, smallpox is the only human infectious disease to have been completely eradicated.

Measles

Historically, measles was prevalent throughout the world, as it is highly contagious. According to the National Immunization Program, 90% of people were infected with measles by age 15. Before the vaccine was introduced in 1963, there were an estimated 3-4 million cases in the U.S. each year. In roughly the last 150 years, measles has been estimated to have killed about 200 million people worldwide. In 2000 alone, measles killed some 777,000 worldwide. There were some 40 million cases of measles globally that year.

Measles is an endemic disease, meaning that it has been continually present in a community, and many people develop resistance. In populations that have not been exposed to measles, exposure to a new disease can be devastating. In 1529, a measles outbreak in Cuba killed two-thirds of the natives who had previously survived smallpox. The disease had ravaged Mexico, Central America, and the Inca civilization.

Tuberculosis

One-third of the world's current population has been infected with *Mycobacterium tuberculosis*, and new infections occur at a rate of one per second. About 5-10% of these latent infections will eventually progress to active disease, which, if left untreated, kills more than half of its victims. Annually, 8 million people become ill with tuberculosis, and 2 million people die from the disease worldwide. In the 19th century, tuberculosis killed an estimated one-quarter of the adult population of Europe; and by 1918 one in six deaths in France were still caused by TB. By the late 19th century, 70 to 90% of the urban populations of Europe and North America were infected with *M. tuberculosis*, and about 40% of working-class deaths in cities were from TB. During the 20th century, tuberculosis killed approximately 100 million people. TB is still one of the most important health problems in the developing world.

Leprosy

Leprosy, also known as Hansen's Disease, is caused by a bacillus, *Mycobacterium leprae*. It is a chronic disease with an incubation period of up to five years. Since 1985, 15 million people worldwide have been cured of leprosy. In 2002, 763,917 new cases were detected. It is estimated that there are between one and two million people permanently disabled because of leprosy.

Historically, leprosy has affected people since at least 600 BCE, and was well-recognized in the civilizations of ancient China, Egypt and India. During the High Middle Ages, Western Europe witnessed an unprecedented outbreak of leprosy. Numerous *leprosaria*, or leper hospitals, sprang up in the Middle Ages; Matthew Paris estimated that in the early 13th century there were 19,000 across Europe.

Malaria

Malaria is widespread in tropical and subtropical regions, including parts of the Americas, Asia, and Africa. Each year, there are approximately 350–500 million cases of malaria. Drug resistance poses a growing problem in the treatment of malaria in the 21st century, since resistance is now common against all classes of antimalarial drugs, except for the artemisinins.

Malaria was once common in most of Europe and North America, where it is now for all purposes non-existent. Malaria may have contributed to the decline of the Roman Empire. The disease became known as "Roman fever". *Plasmodium falciparum* became a real threat to colonists and indigenous people alike when it was introduced into the Americas along with the slave trade. Malaria devastated the Jamestown colony and regularly ravaged the South and Midwest. By 1830 it had reached the Pacific Northwest. During the American Civil War, there were over 1.2 million cases of malaria among soldiers of both sides. The southern U.S. continued to be afflicted with millions of cases of malaria into the 1930s.

Yellow fever

Yellow fever has been a source of several devastating epidemics. Cities as far north as New York, Philadelphia, and Boston were hit with epidemics. In 1793, one of the largest yellow fever epidemics in U.S. history killed as many as 5,000 people in Philadelphia—roughly 10% of the population. About half of the residents had fled the city, including President George Washington. Approximately 300,000 people are believed to have died from yellow fever in Spain during the 19th century. In colonial times, West Africa became known as "the white man's grave" because of malaria and yellow fever.

Unknown causes

There are also a number of unknown diseases that were extremely serious but have now vanished, so the etiology of these diseases cannot be established. The cause of *English Sweat* in 16th-century England, which struck people down in an instant and was more greatly feared than even the bubonic plague, is still unknown.

Concern about possible future pandemics

Viral hemorrhagic fevers

Some Viral Hemorrhagic Fever causing agents like Lassa fever, Rift Valley fever, Marburg virus, Ebola virus and Bolivian hemorrhagic fever are highly contagious and deadly diseases, with the theoretical potential to become pandemics. Their ability to spread efficiently enough to cause a pandemic is limited, however, as transmission of these viruses requires close contact with the infected vector, and the vector only has a short time before death or serious illness. Furthermore, the short time between a vector

becoming infectious and the onset of symptoms allows medical professionals to quickly quarantine vectors, and prevent them from carrying the pathogen elsewhere. Genetic mutations could occur, which could elevate their potential for causing widespread harm; thus close observation by contagious disease specialists is merited.

Antibiotic resistance

Antibiotic-resistant microorganisms, sometimes referred to as "superbugs", may contribute to the re-emergence of diseases which are currently well-controlled. For example, cases of tuberculosis that are resistant to traditionally effective treatments remain a cause of great concern to health professionals. Every year, nearly half a million new cases of multidrug-resistant tuberculosis (MDR-TB) are estimated to occur worldwide. China and India have the highest rate of multidrug-resistant TB. The World Health Organization (WHO) reports that approximately 50 million people worldwide are infected with MDR TB, with 79 percent of those cases resistant to three or more antibiotics. In 2005, 124 cases of MDR TB were reported in the United States. Extensively drug-resistant tuberculosis (XDR TB) was identified in Africa in 2006, and subsequently discovered to exist in 49 countries, including the United States. There are about 40,000 new cases of XDR-TB per year, the WHO estimates.

In the past 20 years, common bacteria including *Staphylococcus aureus*, *Serratia marcescens* and Enterococcus, have developed resistance to various antibiotics such as vancomycin, as well as whole classes of antibiotics, such as the aminoglycosides and cephalosporins. Antibiotic-resistant organisms have become an important cause of healthcare-associated (nosocomial) infections (HAI). In addition, infections caused by community-acquired strains of methicillin-resistant *Staphylococcus aureus* (MRSA) in otherwise healthy individuals have become more frequent in recent years.

Inappropriate antibiotic treatment and overuse of antibiotics have been an element in the emergence of resistant bacteria. The problem is further exacerbated by self-prescribing of antibiotics by individuals without the guidelines of a qualified clinician and the non-therapeutic use of antibiotics as growth promoters in agriculture.

SARS

In 2003, there were concerns that Severe Acute Respiratory Syndrome (SARS), a new and highly contagious form of atypical pneumonia, might become pandemic. It is caused by a coronavirus dubbed SARS-CoV. Rapid action by national and international health authorities such as the World Health Organization helped to slow transmission and eventually broke the chain of transmission. That ended the localized epidemics before they could become a pandemic. However, the disease has not been eradicated. It could re-emerge. This warrants monitoring and reporting of suspicious cases of atypical pneumonia.

Influenza

Wild aquatic birds are the natural hosts for a range of influenza A viruses. Occasionally, viruses are transmitted from these species to other species, and may then cause outbreaks in domestic poultry or, rarely, in humans.

H5N1 (Avian Flu)

In February 2004, avian influenza virus was detected in birds in Vietnam, increasing fears of the emergence of new variant strains. It is feared that if the avian influenza virus combines with a human influenza virus (in a bird or a human), the new subtype created could be both highly contagious and highly lethal in humans. Such a subtype could cause a global influenza pandemic, similar to the Spanish Flu, or the lower mortality pandemics such as the Asian Flu and the Hong Kong Flu.

From October 2004 to February 2005, some 3,700 test kits of the 1957 Asian Flu virus were accidentally spread around the world from a lab in the US.

In May 2005, scientists urgently call nations to prepare for a global influenza pandemic that could strike as much as 20% of the world's population.

In October 2005, cases of the avian flu (the deadly strain H5N1) were identified in Turkey. EU Health Commissioner Markos Kyprianou said: "We have received now confirmation that the virus found in Turkey is an avian flu H5N1 virus. There is a direct relationship with viruses found in Russia, Mongolia and China." Cases of bird flu were also identified shortly thereafter in Romania, and then Greece. Possible cases of the virus have also been found in Croatia, Bulgaria and the United Kingdom.

By November 2007, numerous confirmed cases of the H5N1 strain had been identified across Europe. However, by the end of October only 59 people had died as a result of H5N1 which was atypical of previous influenza pandemics.

Avian flu cannot yet be categorized as a "pandemic", because the virus cannot yet cause sustained and efficient human-to-human transmission. Cases so far are recognized to have been transmitted from bird to human, but as of December 2006 there have been very few (if any) cases of proven human-to-human transmission. Regular influenza viruses establish infection by attaching to receptors in the throat and lungs, but the avian influenza virus can only attach to receptors located deep in the lungs of humans, requiring close, prolonged contact with infected patients, and thus limiting person-to-person transmission.

Biological warfare

In 1346, the bodies of Mongol warriors who had died of plague were thrown over the walls of the besieged Crimean city of Kaffa (now Theodosia). After a protracted siege, during which the Mongol army under Jani Beg was suffering the disease, they catapulted

the infected corpses over the city walls to infect the inhabitants. It has been speculated that this operation may have been responsible for the arrival of the Black Death in Europe.

The Native American population was devastated after contact with the Old World due to the introduction of many different fatal diseases. There is, however, only one documented case of germ warfare, involving British commander Jeffrey Amherst and Swiss-British officer Colonel Henry Bouquet, whose correspondence included a reference to the idea of giving smallpox-infected blankets to Indians as part of an incident known as Pontiac's Rebellion which occurred during the Siege of Fort Pitt (1763) late in the French and Indian War. It is uncertain whether this documented British attempt successfully infected the Indians.

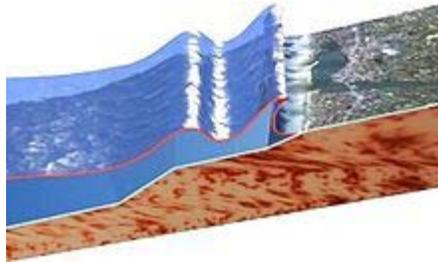
During the Sino-Japanese War (1937–1945), Unit 731 of the Imperial Japanese Army conducted human experimentation on thousands, mostly Chinese. In military campaigns, the Japanese army used biological weapons on Chinese soldiers and civilians. Plague fleas, infected clothing, and infected supplies encased in bombs were dropped on various targets. The resulting cholera, anthrax, and plague were estimated to have killed around 400,000 Chinese civilians.

Diseases considered for or known to be used as a weapon include anthrax, ebola, Marburg virus, plague, cholera, typhus, Rocky Mountain spotted fever, tularemia, brucellosis, Q fever, machupo, Coccidioides mycosis, Glanders, Melioidosis, Shigella, Psittacosis, Japanese B encephalitis, Rift Valley fever, yellow fever, and smallpox.

Spores of weaponized anthrax were accidentally released from a military facility near the Soviet closed city of Sverdlovsk in 1979. The Sverdlovsk anthrax leak is sometimes called "biological Chernobyl". China possibly suffered a serious accident at one of its biological weapons plants in the late 1980s. The Soviets suspected that two separate epidemics of hemorrhagic fever that swept the region in the late 1980s were caused by an accident in a lab where Chinese scientists were weaponizing viral diseases. In January 2009, an Al-Qaeda training camp in Algeria was reportedly wiped out by the plague, killing approximately 40 Islamic extremists. Some experts said that the group was developing biological weapons, however, a couple of days later the Algerian Health Ministry flatly denied this rumour stating "No case of plague of any type has been recorded in any region of Algeria since 2003".

Chapter-3

Megatsunami



An artist's rendering of wave shoaling of a tsunami.

Megatsunami (also known as *iminami* or "purification wave") is an informal term to describe a tsunami that has initial wave heights that are much larger than normal tsunamis. Unlike usual tsunamis, which originate from tectonic activity and the raising or lowering of the sea floor, known megatsunamis have originated from large scale landslides or impact events.

Concept

A megatsunami is meant to refer to a tsunami with an initial wave amplitude (height) measured in several tens, hundreds, or possibly thousands of meters.

Normal tsunamis generated at sea result from movement of the sea floor. They have a small wave height offshore, and a very long wavelength (often hundreds of kilometers long), and generally pass unnoticed at sea, forming only a slight swell usually of the order of 30 cm (12 in) above the normal sea surface. When they reach land the wave height increases dramatically as the base of the wave pushes the water column above it upwards.

By contrast, megatsunamis are caused by giant landslides and other impact events. Underwater earthquakes or volcanic eruptions do not normally generate such large tsunamis, but landslides next to bodies of water resulting from earthquakes can, since they cause a massive amount of displacement. If the landslide or impact occurs in a limited body of water, as happened at the Vajont Dam (1963) and Lituya Bay (1958) then the water may be unable to disperse and one or more exceedingly large waves may result.

Two heights are sometimes quoted for megatsunamis - the height of the wave itself (in water), and the height to which it washes when it reaches land, which depending upon the locale, can be several times larger.

History of the hypothesis

Geologists searching for oil in Alaska in 1953 observed that in Lituya Bay, mature tree growth did not extend to the shoreline as it did in many other bays in the region. Rather, there was a band of younger trees closer to the shore. Forestry workers, glaciologists, and geographers call the boundary between these bands a trim line. Trees just above the trim line showed severe scarring on their seaward side, whilst those from below the trim line did not. The scientists hypothesized that there had been an unusually large wave or waves in the deep inlet. Because this is a recently deglaciated fjord with steep slopes and crossed by a major fault, one possibility was a landslide-generated tsunami.

On 9 July 1958, an earthquake of magnitude 7.7 (on the Richter scale), caused 90 million tonnes of rock and ice to drop into the deep water at the head of Lituya Bay. The block fell almost vertically and hit the water with sufficient force to create a wave approximately 524 metres (1,719 ft) high. Howard Ulrich and his son, Howard Jr., were in the bay in their fishing boat when they saw the wave. They both survived and reported that the wave carried their boat "over the trees" on one of the initial waves which washed them back into the bay, though the larger wave did not harm them a great lot. A similar tsunami out at sea could come tens of kilometers inland.

This event and evidence of a potentially similar past event at the same location inspired the term *megatsunami*.

List of megatsunami

Prehistoric

- The asteroid which created the Chicxulub crater in Yucatan approximately 65 million years BP would have generated some of the largest megatsunami in Earth's history.
- A series of megatsunami were generated by the bolide impact that created the Chesapeake Bay impact crater, about 35.5 million years BP.
- At Seton Portage, British Columbia, Canada, a freshwater megatsunami may have occurred approximately 10,000 BP. A huge block of the Cayoosh Range suddenly slid northwards into what had been a large lake spanning the area from Lillooet, British Columbia to near Birken, in the Gates Valley or Pemberton Pass to the southwest. The event has not been studied in detail, but the proto-lake (freshwater fjord) may have been at least as deep as the two present-day halves, Seton and Anderson Lakes, on either side of the Portage, suggesting that the surge generated by the giant landslide in the narrow mountain confines of the fjord valley may have been comparable in scale to Lituya Bay. Another more recent landslide on

the south shore of Anderson Lake dropped a large portion of high mountainside down a debris chute, creating a rockwall "fan" which *must* have made a megatsunami-type wave, though not as large as the main one at the Portage.

- Approximately 8,000 BP, a massive volcanic landslide off of Mt. Etna, Sicily caused a megatsunami which devastated the eastern Mediterranean coastline on three continents.
- In the Norwegian Sea, the Storegga Slide caused a megatsunami approximately 7,000 years BP.
- Approximately 6000 years ago, a landslide on Réunion island, to the east of Madagascar, may have caused a megatsunami.
- The recently discovered undersea Burckle Crater located at the bottom of the Indian Ocean would have caused a megatsunami at the time of impact estimated to be c. 3000–2800 BCE. It is unknown whether the Burckle Crater is connected to the Fenambosy Chevron which provides evidence of another megatsunami.
- Evidence for large landslides has been found in the form of extensive underwater debris aprons around many volcanic ocean islands which are composed of the material which has slid into the ocean. The island of Molokai had a catastrophic collapse over a million years ago; this underwater landslide likely caused large tsunamis. In recent years, five such debris aprons have been located around the Hawaiian Islands. The Canary Islands have at least 14 such debris aprons associated with the archipelago.

Modern

1792: Mount Unzen, Japan

In 1792, Mount Unzen in Japan erupted, causing part of the volcano to collapse into the sea. The landslide caused a megatsunami that reached 100 meters (328 ft) high and killed 15,000 people in the local fishing villages.

1958: Lituya Bay, Alaska, USA



Damage from the 1958 Lituya Bay megatsunami can be seen in this oblique aerial photograph of Lituya Bay, Alaska as the lighter areas at the shore where trees have been stripped away.

On 9 July 1958, a giant landslide at the head of Lituya Bay in Alaska, caused by an earthquake, generated a wave with an initial amplitude of 524 meters (1,719 ft). This is the highest wave ever recorded, and surged over the headland opposite, stripping trees and soil down to bedrock, and surged along the fjord which forms Lituya Bay, destroying a fishing boat anchored there and killing two people. Howard Ulrich and his son managed to ride the wave in their boat, and both survived.

1963: Vajont Dam, Italy

On 9 October 1963, a landslide above Vajont Dam in Italy produced a 250 m (820 ft) surge that overtopped the dam and destroyed the villages of Longarone, Pirago, Rivalta, Villanova and Faè, killing nearly 2,000 people.

1980: Spirit Lake, Washington, USA

On May 18, 1980, the upper 460 meters of Mount St. Helens failed and detached in a massive landslide. This released the pressure on the magma trapped beneath the summit bulge which exploded as a lateral blast, which then released the over-pressure on the magma chamber and resulted in a plinian eruption.

One lobe of the avalanche surged onto Spirit Lake, causing a megatsunami which pushed the lake waters in a series of surges, which reached a maximum height of 260 metres above the pre-eruption water level (~975 m asl). Above the upper limit of the tsunami, trees lie where they were knocked down by the pyroclastic surge; below the limit, the fallen trees and the surge deposits were removed by the megatsunami and deposited in Spirit Lake.

Potential future megatsunami

Experts interviewed by the BBC think that a massive landslide on a volcanic ocean island is the most likely future cause of a megatsunami. The size and power of a wave generated by such means could produce devastating effects, travelling across oceans and inundating up to 25 kilometres (16 mi) inland from the coast.

British Columbia

Some geologists consider an unstable rock face at Mount Breakenridge, above the north end of the giant fresh-water fjord of Harrison Lake in the Fraser Valley of southwestern British Columbia, Canada, to be unstable enough to collapse into the lake, generating a megatsunami that might destroy the town of Harrison Hot Springs (located at its south end).

Canary Islands

Geologists S. Day and S. Ward consider that a megatsunami could be generated during a future eruption involving the Cumbre Vieja on the volcanic ocean island of La Palma, in the Canary Islands.

In 1949, the Cumbre Vieja volcano erupted at its Duraznero, Hoyo Negro and San Juan vents. During this eruption, an earthquake with an epicentre near the village of Jedy occurred. The following day Rubio Bonelli, a local geologist, visited the summit area and discovered that a fissure about 2.5 kilometers (2 mi) long had opened on the eastern side of the summit. As a result, the western half of the Cumbre Vieja (which is the volcanically active arm of a triple-armed rift) had slipped about 2 meters (7 ft) downwards and 1 meters (3 ft) westwards towards the Atlantic Ocean.

The Cumbre Vieja volcano is currently in a dormant stage, but will almost certainly erupt again in the future. Day and Ward hypothesize that if such an eruption causes the western flank to fail, a megatsunami will be generated.

La Palma is currently the most volcanically active island in the Canary Islands Archipelago. It is likely that several eruptions would be required before failure would occur on Cumbre Vieja. However, the western half of the volcano has an approximate volume of 500 cubic kilometres (120 cu mi) and an estimated mass of 1,500,000,000,000 metric tons (1.7×10^{12} short tons). If it were to catastrophically slide into the ocean, it could generate a wave with an initial height of about 1,000 metres (3,300 ft) at the island, and a likely height of around 50 metres (164 ft) at the Caribbean and the Eastern North American seaboard when it runs ashore eight or more hours later. Tens of millions of lives would be lost as New York, Boston, Baltimore, Washington, D.C., Miami, Havana, and many other cities near the Atlantic coast are leveled. The likelihood of this happening is a matter of vigorous debate.

The last Cumbre Vieja eruption occurred in 1971 at the southern end of the sub-aerial section without any movement. The section affected by the 1949 eruption is currently stationary and does not appear to have moved since the initial rupture.

Geologists and volcanologists also disagree about whether an eruption on the Cumbre Vieja would cause a single large gravitational landslide or a series of smaller landslides.

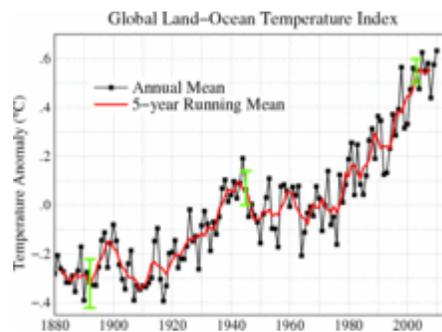
Hawaii

Prehistoric sedimentary deposits on the Kohala Volcano, Lanai and Molokai controversially indicates that landslides from the flank of the Kilauea and Mauna Loa volcanoes in Hawaii may have triggered past megatsunamis, most recently at 120,000 BP. A future tsunami event is also possible, with the tsunami potentially reaching up to about 1 kilometre (3,300 ft) in height. According to a documentary called National Geographic's Ultimate Disaster: Tsunami, if a big landslide occurred at Mauna Loa, a 30 metres (98 ft) tsunami would take only thirty minutes to reach Honolulu, Hawaii.

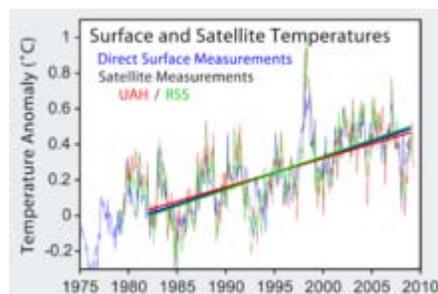
There, hundreds of thousands of people would be killed as the tsunami leveled Honolulu and traveled 25 kilometres (16 mi) inland.

Chapter-4

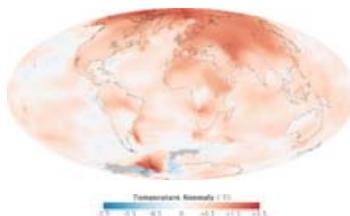
Global Warming



Line plot of global mean land-ocean temperature change from 1880-2010, relative to the 1951-1980 mean. The black line is the annual mean and the red line is the 5-year running mean. The green bars show uncertainty estimates. Source: NASA GISS



Comparison of surface based (blue) and satellite based (red: UAH; green: RSS) records of global mean temperature change from 1979-2009. Linear trends plotted since 1982.



The map shows the 10-year average (2000-2009) global mean temperature anomaly relative to the 1951-1980 mean. The largest temperature increases are in the Arctic and the Antarctic Peninsula. Source: NASA Earth Observatory

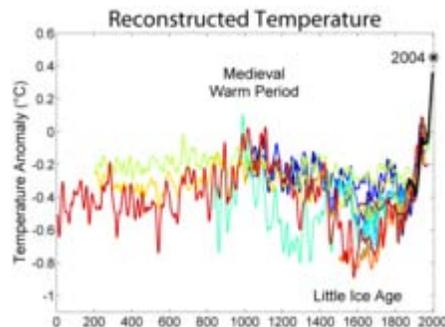
Global warming is the increase in the average temperature of Earth's near-surface air and oceans since the mid-20th century and its projected continuation. According to the 2007 Fourth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC), global surface temperature increased by 0.74 ± 0.18 °C (1.33 ± 0.32 °F) during the 20th century. Most of the observed temperature increase since the middle of the 20th century has been caused by increasing concentrations of greenhouse gases, which result from human activities such as the burning of fossil fuel and deforestation. Global dimming, a reduction of sunlight reaching the surface as a result of increasing atmospheric concentrations of human-made particulates, has partially countered the effects of warming induced by greenhouse gases.

Climate model projections summarized in the 2007 IPCC report indicate that the global surface temperature is likely to rise a further 1.1 to 6.4 °C (2.0 to 11.5 °F) during the 21st century. The uncertainty in this estimate arises from the use of models with differing sensitivity to greenhouse gas concentrations and the use of differing estimates of future greenhouse gas emissions. An increase in global temperature will cause sea levels to rise and will change the amount and pattern of precipitation, probably including expansion of subtropical deserts. Warming is expected to be strongest in the Arctic and would be associated with continuing retreat of glaciers, permafrost and sea ice. Other likely effects of the warming include more frequent and intense precipitation events, extreme weather events, species extinctions due to shifting isotherms, and changes in agricultural yields. Warming and related changes will vary from region to region around the globe, though the nature of these regional changes is uncertain. As a result of contemporary increases in atmospheric carbon dioxide, the oceans have become more acidic, a result that is predicted to continue.

The scientific consensus is that anthropogenic global warming is occurring. This finding is recognized by the national science academies of all the major industrialized countries and is not rejected by any scientific body of national or international standing. According to a recent Gallup poll, "People nearly everywhere, including majorities in developed Asia and Latin America, are more likely to attribute global warming to human activities rather than natural causes. The U.S. is the exception, with nearly half (47%) -- and the largest percentage in the world -- attributing global warming to natural causes."

The Kyoto Protocol is aimed at stabilizing greenhouse gas concentration to prevent a "dangerous anthropogenic interference". As of November 2009, 187 states had signed and ratified the protocol. Proposed responses to global warming include mitigation to reduce emissions, adaptation to the effects of global warming, and geoengineering to remove greenhouse gases from the atmosphere.

Temperature changes



Two millennia of mean surface temperatures according to different reconstructions, each smoothed on a decadal scale, with the instrumental temperature record overlaid in black.

Evidence for warming of the climate system includes observed increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level. The most common measure of global warming is the trend in globally averaged temperature near the Earth's surface. Expressed as a linear trend, this temperature rose by 0.74 ± 0.18 °C over the period 1906–2005. The rate of warming over the last half of that period was almost double that for the period as a whole (0.13 ± 0.03 °C per decade, versus 0.07 °C \pm 0.02 °C per decade). The urban heat island effect is estimated to account for about 0.002 °C of warming per decade since 1900. Temperatures in the lower troposphere have increased between 0.13 and 0.22 °C (0.22 and 0.4 °F) per decade since 1979, according to satellite temperature measurements. Temperature is believed to have been relatively stable over the one or two thousand years before 1850, with regionally varying fluctuations such as the Medieval Warm Period and the Little Ice Age.

Recent estimates by NASA's Goddard Institute for Space Studies (GISS) and the National Climatic Data Center show that 2005 and 2010 tied for the planet's warmest year since reliable, widespread instrumental measurements became available in the late 19th century, exceeding 1998 by a few hundredths of a degree. Current estimates by the Climatic Research Unit (CRU) show 2005 as the second warmest year, behind 1998 with 2003 and 2010 tied for third warmest year, however, "the error estimate for individual years ... is at least ten times larger than the differences between these three years." The World Meteorological Organization (WMO) *statement on the status of the global climate in 2010* explains that, "The 2010 nominal value of $+0.53$ °C ranks just ahead of those of 2005 ($+0.52$ °C) and 1998 ($+0.51$ °C), although the differences between the three years are not statistically significant..."

Temperatures in 1998 were unusually warm because the strongest El Niño in the past century occurred during that year. Global temperature is subject to short-term fluctuations that overlay long term trends and can temporarily mask them. The relative stability in temperature from 2002 to 2009 is consistent with such an episode.

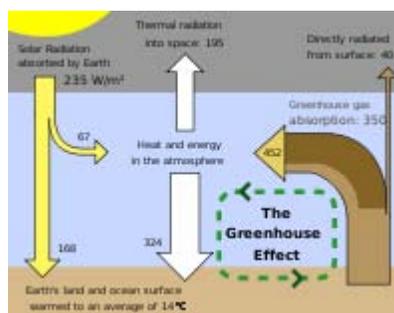
Temperature changes vary over the globe. Since 1979, land temperatures have increased about twice as fast as ocean temperatures (0.25 °C per decade against 0.13 °C per decade). Ocean temperatures increase more slowly than land temperatures because of the larger effective heat capacity of the oceans and because the ocean loses more heat by evaporation. The Northern Hemisphere warms faster than the Southern Hemisphere because it has more land and because it has extensive areas of seasonal snow and sea-ice cover subject to ice-albedo feedback. Although more greenhouse gases are emitted in the Northern than Southern Hemisphere this does not contribute to the difference in warming because the major greenhouse gases persist long enough to mix between hemispheres.

The thermal inertia of the oceans and slow responses of other indirect effects mean that climate can take centuries or longer to adjust to changes in forcing. Climate commitment studies indicate that even if greenhouse gases were stabilized at 2000 levels, a further warming of about 0.5 °C (0.9 °F) would still occur.

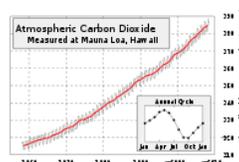
External forcings

External forcing refers to processes external to the climate system (though not necessarily external to Earth) that influence climate. Climate responds to several types of external forcing, such as radiative forcing due to changes in atmospheric composition (mainly greenhouse gas concentrations), changes in solar luminosity, volcanic eruptions, and variations in Earth's orbit around the Sun. Attribution of recent climate change focuses on the first three types of forcing. Orbital cycles vary slowly over tens of thousands of years and thus are too gradual to have caused the temperature changes observed in the past century.

Greenhouse gases



Greenhouse effect schematic showing energy flows between space, the atmosphere, and earth's surface. Energy exchanges are expressed in watts per square meter (W/m^2).



This graph is known as the "Keeling Curve" and it shows the long-term increase of atmospheric carbon dioxide (CO₂) concentrations from 1958-2008. Monthly CO₂ measurements display seasonal oscillations in an upward trend; each year's maximum occurs during the Northern Hemisphere's late spring, and declines during its growing season as plants remove some atmospheric CO₂.

The greenhouse effect is the process by which absorption and emission of infrared radiation by gases in the atmosphere warm a planet's lower atmosphere and surface. It was proposed by Joseph Fourier in 1824 and was first investigated quantitatively by Svante Arrhenius in 1896.

Naturally occurring greenhouse gases have a mean warming effect of about 33 °C (59 °F). The major greenhouse gases are water vapor, which causes about 36–70 percent of the greenhouse effect; carbon dioxide (CO₂), which causes 9–26 percent; methane (CH₄), which causes 4–9 percent; and ozone (O₃), which causes 3–7 percent. Clouds also affect the radiation balance, but they are composed of liquid water or ice and so have different effects on radiation from water vapor.

Human activity since the Industrial Revolution has increased the amount of greenhouse gases in the atmosphere, leading to increased radiative forcing from CO₂, methane, tropospheric ozone, CFCs and nitrous oxide. The concentrations of CO₂ and methane have increased by 36% and 148% respectively since 1750. These levels are much higher than at any time during the last 800,000 years, the period for which reliable data has been extracted from ice cores. Less direct geological evidence indicates that CO₂ values higher than this were last seen about 20 million years ago. Fossil fuel burning has produced about three-quarters of the increase in CO₂ from human activity over the past 20 years. The rest of this increase is caused mostly by changes in land-use, particularly deforestation.

Over the last three decades of the 20th century, GDP per capita and population growth were the main drivers of increases in greenhouse gas emissions. CO₂ emissions are continuing to rise due to the burning of fossil fuels and land-use change.⁷¹ Emissions scenarios, estimates of changes in future emission levels of greenhouse gases, have been projected that depend upon uncertain economic, sociological, technological, and natural developments. In most scenarios, emissions continue to rise over the century, while in a few, emissions are reduced. These emission scenarios, combined with carbon cycle modelling, have been used to produce estimates of how atmospheric concentrations of greenhouse gases will change in the future. Using the six IPCC SRES "marker" scenarios, models suggest that by the year 2100, the atmospheric concentration of CO₂ could range between 541 and 970 ppm. This is an increase of 90-250% above the concentration in the year 1750. Fossil fuel reserves are sufficient to reach these levels and continue emissions past 2100 if coal, oil sands or methane clathrates are extensively exploited.

The popular media and the public often confuse global warming with the ozone hole, i.e., the destruction of stratospheric ozone by chlorofluorocarbons. Although there are a few areas of linkage, the relationship between the two is not strong. Reduced stratospheric ozone has had a slight cooling influence on surface temperatures, while increased tropospheric ozone has had a somewhat larger warming effect.

Particulates and soot



Ship tracks over the Atlantic Ocean on the east coast of the United States. The climatic impacts from particulate forcing could have a large effect on climate through the indirect effect.

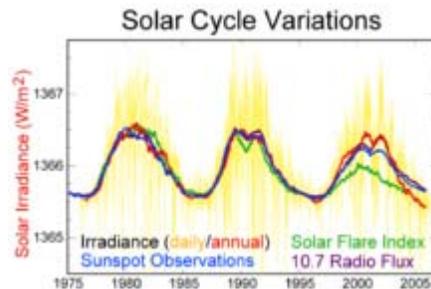
Global dimming, a gradual reduction in the amount of global direct irradiance at the Earth's surface, has partially counteracted global warming from 1960 to the present. The main cause of this dimming is particulates produced by volcanoes and pollutants, which exerts a cooling effect by increasing the reflection of incoming sunlight. The effects of the products of fossil fuel combustion—CO₂ and aerosols—have largely offset one another in recent decades, so that net warming has been due to the increase in non-CO₂ greenhouse gases such as methane. Radiative forcing due to particulates is temporally limited due to wet deposition which causes them to have an atmospheric lifetime of one week. Carbon dioxide has a lifetime of a century or more, and as such, changes in particulate concentrations will only delay climate changes due to carbon dioxide.

In addition to their direct effect by scattering and absorbing solar radiation, particulates have indirect effects on the radiation budget. Sulfates act as cloud condensation nuclei and thus lead to clouds that have more and smaller cloud droplets. These clouds reflect solar radiation more efficiently than clouds with fewer and larger droplets, known as the Twomey effect. This effect also causes droplets to be of more uniform size, which reduces growth of raindrops and makes the cloud more reflective to incoming sunlight, known as the Albrecht effect. Indirect effects are most noticeable in marine stratiform clouds, and have very little radiative effect on convective clouds. Indirect effects of particulates represent the largest uncertainty in radiative forcing.

Soot may cool or warm the surface, depending on whether it is airborne or deposited. Atmospheric soot directly absorb solar radiation, which heats the atmosphere and cools the surface. In isolated areas with high soot production, such as rural India, as much as 50% of surface warming due to greenhouse gases may be masked by atmospheric brown

clouds. When deposited, especially on glaciers or on ice in arctic regions, the lower surface albedo can also directly heat the surface. The influences of particulates, including black carbon, are most pronounced in the tropics and sub-tropics, particularly in Asia, while the effects of greenhouse gases are dominant in the extratropics and southern hemisphere.

Solar variation



Total Solar Irradiance measured by satellite from 1979-2006.

Variations in solar output have been the cause of past climate changes. The effect of changes in solar forcing in recent decades is uncertain, but small, with some studies showing a slight cooling effect, while others studies suggest a slight warming effect.

Greenhouse gases and solar forcing affect temperatures in different ways. While both increased solar activity and increased greenhouse gases are expected to warm the troposphere, an increase in solar activity should warm the stratosphere while an increase in greenhouse gases should cool the stratosphere. Observations show that temperatures in the stratosphere have been cooling since 1979, when satellite measurements became available. Radiosonde (weather balloon) data from the pre-satellite era show cooling since 1958, though there is greater uncertainty in the early radiosonde record.

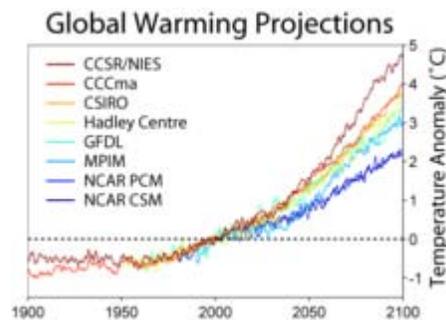
A related hypothesis, proposed by Henrik Svensmark, is that magnetic activity of the sun deflects cosmic rays that may influence the generation of cloud condensation nuclei and thereby affect the climate. Other research has found no relation between warming in recent decades and cosmic rays. The influence of cosmic rays on cloud cover is about a factor of 100 lower than needed to explain the observed changes in clouds or to be a significant contributor to present-day climate change.

Feedback

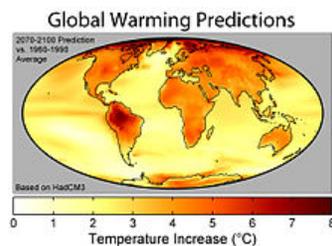
Feedback is a process in which changing one quantity changes a second quantity, and the change in the second quantity in turn changes the first. Positive feedback increases the change in the first quantity while negative feedback reduces it. Feedback is important in the study of global warming because it may amplify or diminish the effect of a particular process. The main positive feedback in global warming is the tendency of warming to increase the amount of water vapor in the atmosphere, a significant greenhouse gas. The

main negative feedback is radiative cooling, which increases as the fourth power of temperature; the amount of heat radiated from the Earth into space increases with the temperature of Earth's surface and atmosphere. Imperfect understanding of feedbacks is a major cause of uncertainty and concern about global warming. A wide range of potential feedback process exist, such as Arctic methane release and ice-albedo feedback. Consequentially, potential tipping points may exist, which may have the potential to cause abrupt climate change.

Climate models



Calculations of global warming prepared in or before 2001 from a range of climate models under the SRES A2 emissions scenario, which assumes no action is taken to reduce emissions and regionally divided economic development.



The geographic distribution of surface warming during the 21st century calculated by the HadCM3 climate model if a business as usual scenario is assumed for economic growth and greenhouse gas emissions. In this figure, the globally averaged warming corresponds to 3.0 °C (5.4 °F).

The main tools for projecting future climate changes are mathematical models based on physical principles including fluid dynamics, thermodynamics and radiative transfer. Although they attempt to include as many processes as possible, simplifications of the actual climate system are inevitable because of the constraints of available computer power and limitations in knowledge of the climate system. All modern climate models are in fact *combinations* of models for different parts of the Earth. These include an atmospheric model for air movement, temperature, clouds, and other atmospheric properties; an ocean model that predicts temperature, salt content, and circulation of ocean waters; models for ice cover on land and sea; and a model of heat and moisture transfer from soil and vegetation to the atmosphere. Some models also include treatments

of chemical and biological processes. Warming due to increasing levels of greenhouse gases is not an assumption of the models; rather, it is an end result from the interaction of greenhouse gases with radiative transfer and other physical processes. Although much of the variation in model outcomes depends on the greenhouse gas emissions used as inputs, the temperature effect of a specific greenhouse gas concentration (climate sensitivity) varies depending on the model used. The representation of clouds is one of the main sources of uncertainty in present-generation models.

Global climate model projections of future climate most often have used estimates of greenhouse gas emissions from the IPCC Special Report on Emissions Scenarios (SRES). In addition to human-caused emissions, some models also include a simulation of the carbon cycle; this generally shows a positive feedback, though this response is uncertain. Some observational studies also show a positive feedback. Including uncertainties in future greenhouse gas concentrations and climate sensitivity, the IPCC anticipates a warming of 1.1 °C to 6.4 °C (2.0 °F to 11.5 °F) by the end of the 21st century, relative to 1980–1999.

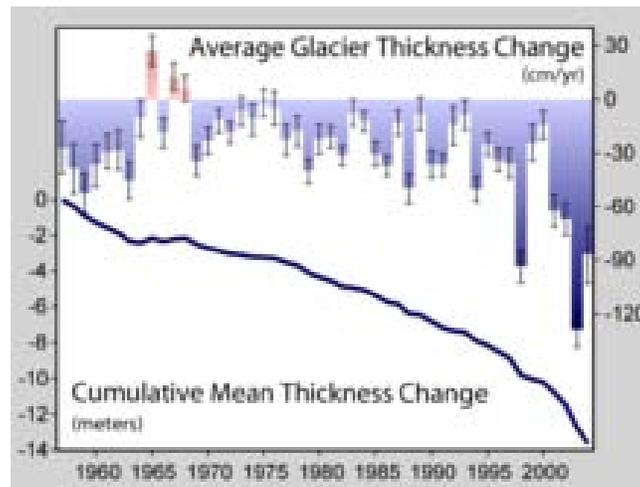
Models are also used to help investigate the causes of recent climate change by comparing the observed changes to those that the models project from various natural and human-derived causes. Although these models do not unambiguously attribute the warming that occurred from approximately 1910 to 1945 to either natural variation or human effects, they do indicate that the warming since 1970 is dominated by man-made greenhouse gas emissions.

The physical realism of models is tested by examining their ability to simulate current or past climates. Current climate models produce a good match to observations of global temperature changes over the last century, but do not simulate all aspects of climate. Not all effects of global warming are accurately predicted by the climate models used by the IPCC. Observed Arctic shrinkage has been faster than that predicted. Precipitation increased proportional to atmospheric humidity, and hence significantly faster than current global climate models predict.

Attributed and expected effects

Global warming may be detected in natural, ecological or social systems as a change having statistical significance. Attribution of these changes e.g., to natural or human activities, is the next step following detection.

Natural systems



Sparse records indicate that glaciers have been retreating since the early 1800s. In the 1950s measurements began that allow the monitoring of glacial mass balance, reported to the WGMS and the NSIDC.

Global warming has been detected in a number of systems. Some of these changes, e.g., based on the instrumental temperature record, have been described in the section on temperature changes. Rising sea levels and observed decreases in snow and ice extent are consistent with warming. Most of the increase in global average temperature since the mid-20th century is, with high probability, attributable to human-induced changes in greenhouse gas concentrations.

Even with current policies to reduce emissions, global emissions are still expected to continue to grow over the coming decades. Over the course of the 21st century, increases in emissions at or above their current rate would very likely induce changes in the climate system larger than those observed in the 20th century.

In the IPCC Fourth Assessment Report, across a range of future emission scenarios, model-based estimates of sea level rise for the end of the 21st century (the year 2090-2099, relative to 1980-1999) range from 0.18 to 0.59 m. These estimates, however, were not given a likelihood due to a lack of scientific understanding, nor was an upper bound given for sea level rise. Over the course of centuries to millennia, the melting of ice sheets could result in sea level rise of 4–6 m or more.

Changes in regional climate are expected to include greater warming over land, with most warming at high northern latitudes, and least warming over the Southern Ocean and parts of the North Atlantic Ocean. Snow cover area and sea ice extent are expected to decrease, with the Arctic expected to be largely ice-free in September by the 2037. The frequency of hot extremes, heat waves, and heavy precipitation will very likely increase.

Ecological systems

In terrestrial ecosystems, the earlier timing of spring events, and poleward and upward shifts in plant and animal ranges, have been linked with high confidence to recent warming. Future climate change is expected to particularly affect certain ecosystems, including tundra, mangroves, and coral reefs. It is expected that most ecosystems will be affected by higher atmospheric CO₂ levels, combined with higher global temperatures. Overall, it is expected that climate change will result in the extinction of many species and reduced diversity of ecosystems.

Social systems

Vulnerability of human societies to climate change mainly lies in the effects of extreme weather events rather than gradual climate change. Impacts of climate change so far include adverse effects on small islands, adverse effects on indigenous populations in high-latitude areas, and small but discernable effects on human health. Over the 21st century, climate change is likely to adversely affect hundreds of millions of people through increased coastal flooding, reductions in water supplies, increased malnutrition and increased health impacts.

Future warming of around 3 °C (by 2100, relative to 1990-2000) could result in increased crop yields in mid- and high-latitude areas, but in low-latitude areas, yields could decline, increasing the risk of malnutrition. A similar regional pattern of net benefits and costs could occur for economic (market-sector) effects. Warming above 3 °C could result in crop yields falling in temperate regions, leading to a reduction in global food production. Most economic studies suggest losses of world gross domestic product (GDP) for this magnitude of warming.

Responses to global warming

Mitigation

Reducing the amount of future climate change is called mitigation of climate change. The IPCC defines mitigation as activities that reduce greenhouse gas (GHG) emissions, or enhance the capacity of carbon sinks to absorb GHGs from the atmosphere. Many countries, both developing and developed, are aiming to use cleaner, less polluting, technologies. Use of these technologies aids mitigation and could result in substantial reductions in CO₂ emissions. Policies include targets for emissions reductions, increased use of renewable energy, and increased energy efficiency. Studies indicate substantial potential for future reductions in emissions. Since even in the most optimistic scenario, fossil fuels are going to be used for years to come, mitigation may also involve carbon capture and storage, a process that traps CO₂ produced by factories and gas or coal power stations and then stores it, usually underground.

Adaptation

Other policy responses include adaptation to climate change. Adaptation to climate change may be planned, e.g., by local or national government, or spontaneous, i.e., done privately without government intervention. The ability to adapt is closely linked to social and economic development. Even societies with high capacities to adapt are still vulnerable to climate change. Planned adaptation is already occurring on a limited basis. The barriers, limits, and costs of future adaptation are not fully understood.

Geoengineering

Another policy response is engineering of the climate (geoengineering). This policy response is sometimes grouped together with mitigation. Geoengineering is largely unproven, and reliable cost estimates for it have not yet been published. Geoengineering encompasses a range of techniques to remove CO₂ from the atmosphere or to block incoming sunlight. As most geoengineering techniques would affect the entire globe, the use of effective techniques, if they can be developed, would require global public acceptance and an adequate global legal and regulatory framework.

UNFCCC

Most countries are Parties to the United Nations Framework Convention on Climate Change (UNFCCC). The ultimate objective of the Convention is to prevent "dangerous" human interference of the climate system. As is stated in the Convention, this requires that GHGs are stabilized in the atmosphere at a level where ecosystems can adapt naturally to climate change, food production is not threatened, and economic development can proceed in a sustainable fashion.

The UNFCCC recognizes differences among countries in their responsibility to act on climate change. In the Kyoto Protocol to the UNFCCC, most developed countries (listed in Annex I of the treaty) took on legally binding commitments to reduce their emissions. Policy measures taken in response to these commitments have reduced emissions. For many developing (non-Annex I) countries, reducing poverty is their overriding aim.

At the 15th UNFCCC Conference of the Parties, held in 2009 at Copenhagen, several UNFCCC Parties produced the Copenhagen Accord. Parties agreeing with the Accord aim to limit the future increase in global mean temperature to below 2 °C. The 16th Conference of the Parties (COP16) was held at Cancún in 2010. It produced an agreement, not a binding treaty, that the Parties should take urgent action to reduce greenhouse gas emissions to meet the 2 °C goal. It also recognized the need to consider strengthening the goal to a global average rise of 1.5 °C.

Views on global warming



Per capita greenhouse gas emissions in 2005, including land-use change.



Total greenhouse gas emissions in 2005, including land-use change.

There are different views over what the appropriate policy response to climate change should be. These competing views weigh the benefits of limiting emissions of greenhouse gases against the costs. In general, it seems likely that climate change will impose greater damages and risks in poorer regions.

Politics

Developed and developing countries have made different arguments over who should bear the burden of economic costs for cutting emissions. Developing countries often concentrate on per capita emissions, that is, the total emissions of a country divided by its population. Per capita emissions in the industrialized countries are typically as much as ten times the average in developing countries. This is used to make the argument that the real problem of climate change is due to the profligate and unsustainable lifestyles of those living in rich countries.

On the other hand, Banuri et al. point out that total carbon emissions, carrying capacity, efficient energy use and civil and political rights are very important issues. Land is not the same everywhere. Not only the quantity of fossil fuel use but also the quality of energy use is a key debate point. Efficient energy use supporting technological change might help reduce excess carbon dioxide in Earth's atmosphere. The use of fossil fuels for conspicuous consumption and excessive entertainment are issues that can conflict with civil and political rights. People in developed countries argue that history has proven the difficulty of implementing fair rationing programs in different countries because there is no global system of checks and balances or civil liberties.

The Kyoto Protocol, which came into force in 2005, sets legally binding emission limitations for most developed countries. Developing countries are not subject to

limitations. This exemption led the U.S. and Australia to decide not to ratify the treaty, although Australia did finally ratify the treaty in December 2007. Debate continued at the Copenhagen climate summit and the Cancún climate summit.

Public opinion

In 2007–2008 Gallup Polls surveyed 127 countries. Over a third of the world's population was unaware of global warming, with people in developing countries less aware than those in developed, and those in Africa the least aware. Of those aware, Latin America leads in belief that temperature changes are a result of human activities while Africa, parts of Asia and the Middle East, and a few countries from the Former Soviet Union lead in the opposite belief. In the Western world, opinions over the concept and the appropriate responses are divided. Nick Pidgeon of Cardiff University said that "results show the different stages of engagement about global warming on each side of the Atlantic", adding, "The debate in Europe is about what action needs to be taken, while many in the U.S. still debate whether climate change is happening." A 2010 poll by the Office of National Statistics found that 75% of UK respondents were at least "fairly convinced" that the world's climate is changing, compared to 87% in a similar survey in 2006. A January 2011 ICM poll in the UK found 83% of respondents viewed climate change as a current or imminent threat, while 14% said it was no threat. Opinion was unchanged from an August 2009 poll asking the same question, though there had been a slight polarisation of opposing views.

A survey in October, 2009 by the Pew Research Center for the People & the Press showed decreasing public perception in the United States that global warming was a serious problem. All political persuasions showed reduced concern with lowest concern among Republicans, only 35% of whom considered there to be solid evidence of global warming. The cause of this marked difference in public opinion between the United States and the global public is uncertain but the hypothesis has been advanced that clearer communication by scientists both directly and through the media would be helpful in adequately informing the American public of the scientific consensus and the basis for it. The U.S. public appears to be unaware of the extent of scientific consensus regarding the issue, with 59% believing that scientists disagree "significantly" on global warming.

By 2010, with 111 countries surveyed, Gallup determined that there was a substantial decrease in the number of Americans and Europeans who viewed Global Warming as a serious threat. In the United States, a little over half the population (53%) now viewed it as a serious concern for either themselves or their families; a number 10 percentage points below the 2008 poll (63%). Latin America had the biggest rise in concern, with 73% saying global warming was a serious threat to their families.

Other views

Most scientists accept that humans are contributing to observed climate change. National science academies have called on world leaders for policies to cut global emissions. However, some scientists and non-scientists question aspects of climate-change science.

Organizations such as the libertarian Competitive Enterprise Institute, conservative commentators, and some companies such as ExxonMobil have challenged IPCC climate change scenarios, funded scientists who disagree with the scientific consensus, and provided their own projections of the economic cost of stricter controls. In the finance industry, Deutsche Bank has set up an institutional climate change investment division (DBCCA), which has commissioned and published research on the issues and debate surrounding global warming. Environmental organizations and public figures have emphasized changes in the current climate and the risks they entail, while promoting adaptation to changes in infrastructural needs and emissions reductions. Some fossil fuel companies have scaled back their efforts in recent years, or called for policies to reduce global warming.

Etymology

The term *global warming* was probably first used in its modern sense on 8 August 1975 in a science paper by Wally Broecker in the journal *Science* called "Are we on the brink of a pronounced global warming?". Broecker's choice of words was new and represented a significant recognition that the climate was warming; previously the phrasing used by scientists was "inadvertent climate modification," because while it was recognized humans could change the climate, no one was sure which direction it was going. The National Academy of Sciences first used *global warming* in a 1979 paper called the Charney Report, it said: "if carbon dioxide continues to increase, [we find] no reason to doubt that climate changes will result and no reason to believe that these changes will be negligible." The report made a distinction between referring to surface temperature changes as *global warming*, while referring to other changes caused by increased CO₂ as *climate change*.

Global warming became more widely popular after 1988 when NASA climate scientist James Hansen used the term in a testimony to Congress. He said: "global warming has reached a level such that we can ascribe with a high degree of confidence a cause and effect relationship between the greenhouse effect and the observed warming." His testimony was widely reported and afterward *global warming* was commonly used by the press and in public discourse.

Chapter-5

Climate Change

Climate change is a long-term change in the statistical distribution of weather patterns over periods of time that range from decades to millions of years. It may be a change in the average weather conditions, or in a change of the distribution of events around that average (e.g., more or fewer extreme weather events). Climate change may be limited to a specific region, or may occur across the whole Earth.

Terminology

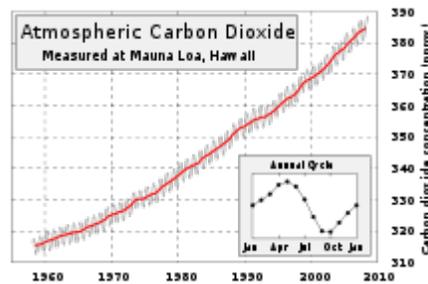
The most general definition of *climate change* is a change in the statistical properties of the climate system when considered over long periods of time, regardless of cause, this type of climate change and its effects have been documented in the past. Accordingly, fluctuations over periods shorter than a few decades, such as El Niño, do not represent climate change.

The term sometimes is used to refer specifically to climate change caused by human activity; for example, the United Nations Framework Convention on Climate Change defines climate change as "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods." In this latter sense, used especially in the context of environmental policy, climate change is synonymous with anthropogenic global warming.

Causes

Factors that can shape climate are climate forcings. These include such processes as variations in solar radiation, deviations in the Earth's orbit, mountain-building and continental drift, and changes in greenhouse gas concentrations. There are a variety of climate change feedbacks that can either amplify or diminish the initial forcing. Some parts of the climate system, such as the oceans and ice caps, respond slowly in reaction to climate forcing because of their large mass. Therefore, the climate system can take centuries or longer to fully respond to new external forcings.

Human influences



Increase in Atmospheric CO₂ Levels

In the context of climate variation, anthropogenic factors are human activities which affect the climate. The scientific consensus on climate change is, "that climate is changing and that these changes are in large part caused by human activities."

“Science has made enormous inroads in understanding climate change and its causes, and is beginning to help develop a strong understanding of current and potential impacts that will affect people today and in coming decades. This understanding is crucial because it allows decision makers to place climate change in the context of other large challenges facing the nation and the world. There are still some uncertainties, and there always will be in understanding a complex system like Earth’s climate. Nevertheless, there is a strong, credible body of evidence, based on multiple lines of research, documenting that climate is changing and that these changes are in large part caused by human activities. While much remains to be learned, the core phenomenon, scientific questions, and hypotheses have been examined thoroughly and have stood firm in the face of serious scientific debate and careful evaluation of alternative explanations.”

Consequently, the debate is shifting onto ways to reduce further human impact and to find ways to adapt to change that has already occurred and is anticipated to occur in the future.

Of most concern in these anthropogenic factors is the increase in CO₂ levels due to emissions from fossil fuel combustion, followed by aerosols (particulate matter in the atmosphere) and cement manufacture. Other factors, including land use, ozone depletion, animal agriculture and deforestation, are also of concern in the roles they play - both separately and in conjunction with other factors - in affecting climate, microclimate, and measures of climate variables.

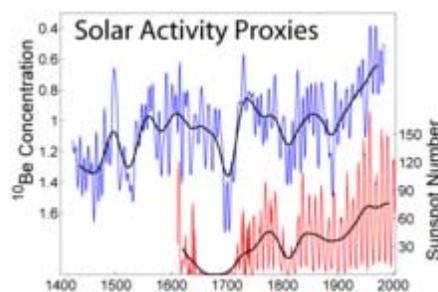
Plate tectonics

Over the course of millions of years, the motion of tectonic plates reconfigures global land and ocean areas and generates topography. This can affect both global and local patterns of climate and atmosphere-ocean circulation.

The position of the continents determines the geometry of the oceans and therefore influences patterns of ocean circulation. The locations of the seas are important in controlling the transfer of heat and moisture across the globe, and therefore, in determining global climate. A recent example of tectonic control on ocean circulation is the formation of the Isthmus of Panama about 5 million years ago, which shut off direct mixing between the Atlantic and Pacific Oceans. This strongly affected the ocean dynamics of what is now the Gulf Stream and may have led to Northern Hemisphere ice cover. During the Carboniferous period, about 300 to 360 million years ago, plate tectonics may have triggered large-scale storage of carbon and increased glaciation. Geologic evidence points to a "megamonsoonal" circulation pattern during the time of the supercontinent Pangaea, and climate modeling suggests that the existence of the supercontinent was conducive to the establishment of monsoons.

The size of continents is also important. Because of the stabilizing effect of the oceans on temperature, yearly temperature variations are generally lower in coastal areas than they are inland. A larger supercontinent will therefore have more area in which climate is strongly seasonal than will several smaller continents or islands.

Solar output



Variations in solar activity during the last several centuries based on observations of sunspots and beryllium isotopes.

The sun is the predominant source for energy input to the Earth. Both long- and short-term variations in solar intensity are known to affect global climate.

Three to four billion years ago the sun emitted only 70% as much power as it does today. If the atmospheric composition had been the same as today, liquid water should not have existed on Earth. However, there is evidence for the presence of water on the early Earth, in the Hadean and Archean eons, leading to what is known as the faint young sun paradox. Hypothesized solutions to this paradox include a vastly different atmosphere, with much higher concentrations of greenhouse gases than currently exist. Over the following approximately 4 billion years, the energy output of the sun increased and atmospheric composition changed, with the oxygenation of the atmosphere around 2.4 billion years ago being the most notable alteration. These changes in luminosity, and the sun's ultimate death as it becomes a red giant and then a white dwarf, will have large effects on climate, with the red giant phase possibly ending life on Earth.

Solar output also varies on shorter time scales, including the 11-year solar cycle and longer-term modulations. Solar intensity variations are considered to have been influential in triggering the Little Ice Age, and some of the warming observed from 1900 to 1950. The cyclical nature of the sun's energy output is not yet fully understood; it differs from the very slow change that is happening within the sun as it ages and evolves. While most research indicates solar variability has induced a small cooling effect from 1750 to the present, a few studies point toward solar radiation increases from cyclical sunspot activity affecting global warming.

Interestingly, a 2010 study *suggests*, “that the effects of solar variability on temperature throughout the atmosphere may be contrary to current expectations.”

Orbital variations

Slight variations in Earth's orbit lead to changes in the seasonal distribution of sunlight reaching the Earth's surface and how it is distributed across the globe. There is very little change to the area-averaged annually averaged sunshine; but there can be strong changes in the geographical and seasonal distribution. The three types of orbital variations are variations in Earth's eccentricity, changes in the tilt angle of Earth's axis of rotation, and precession of Earth's axis. Combined together, these produce Milankovitch cycles which have a large impact on climate and are notable for their correlation to glacial and interglacial periods, their correlation with the advance and retreat of the Sahara, and for their appearance in the stratigraphic record.

Volcanism

Volcanism is a process of conveying material from the crust and mantle of the Earth to its surface. Volcanic eruptions, geysers, and hot springs, are examples of volcanic processes which release gases and/or particulates into the atmosphere.

Eruptions large enough to affect climate occur on average several times per century, and cause cooling (by partially blocking the transmission of solar radiation to the Earth's surface) for a period of a few years. The eruption of Mount Pinatubo in 1991, the second largest terrestrial eruption of the 20th century (after the 1912 eruption of Novarupta) affected the climate substantially. Global temperatures decreased by about 0.5 °C (0.9 °F). The eruption of Mount Tambora in 1815 caused the Year Without a Summer. Much larger eruptions, known as large igneous provinces, occur only a few times every hundred million years, but may cause global warming and mass extinctions.

Volcanoes are also part of the extended carbon cycle. Over very long (geological) time periods, they release carbon dioxide from the Earth's crust and mantle, counteracting the uptake by sedimentary rocks and other geological carbon dioxide sinks. According to the US Geological Survey, however, estimates are that human activities generate 100-300 times the amount of carbon dioxide emitted by volcanoes.

Ocean variability



A schematic of modern thermohaline circulation

The ocean is a fundamental part of the climate system. Short-term fluctuations (years to a few decades) such as the El Niño-Southern Oscillation, the Pacific decadal oscillation, the North Atlantic oscillation, and the Arctic oscillation, represent climate variability rather than climate change. On longer time scales, alterations to ocean processes such as thermohaline circulation play a key role in redistributing heat by carrying out a very slow and extremely deep movement of water, and the long-term redistribution of heat in the world's oceans.

Physical evidence for climatic change

Evidence for climatic change is taken from a variety of sources that can be used to reconstruct past climates. Reasonably complete global records of surface temperature are available beginning from the mid-late 19th century. For earlier periods, most of the evidence is indirect—climatic changes are inferred from changes in proxies, indicators that reflect climate, such as vegetation, ice cores, dendrochronology, sea level change, and glacial geology.

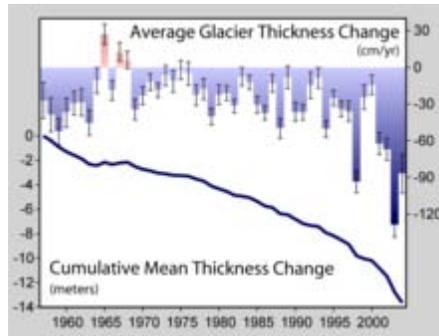
Historical and archaeological evidence

Climate change in the recent past may be detected by corresponding changes in settlement and agricultural patterns. Archaeological evidence, oral history and historical documents can offer insights into past changes in the climate. Climate change effects have been linked to the collapse of various civilisations.

Glaciers



Variations in CO₂, temperature and dust from the Vostok ice core over the last 450,000 years



Decline in thickness of glaciers worldwide

Glaciers are considered among the most sensitive indicators of climate change. Their size is determined by a mass balance between snow input and melt output. As temperatures warm, glaciers retreat unless snow precipitation increases to make up for the additional melt; the converse is also true.

Glaciers grow and shrink due both to natural variability and external forcings. Variability in temperature, precipitation, and englacial and subglacial hydrology can strongly determine the evolution of a glacier in a particular season. Therefore, one must average over a decadal or longer time-scale and/or over a many individual glaciers to smooth out the local short-term variability and obtain a glacier history that is related to climate.

A world glacier inventory has been compiled since the 1970s, initially based mainly on aerial photographs and maps but now relying more on satellites. This compilation tracks more than 100,000 glaciers covering a total area of approximately 240,000 km², and preliminary estimates indicate that the remaining ice cover is around 445,000 km². The World Glacier Monitoring Service collects data annually on glacier retreat and glacier mass balance. From this data, glaciers worldwide have been found to be shrinking significantly, with strong glacier retreats in the 1940s, stable or growing conditions during the 1920s and 1970s, and again retreating from the mid 1980s to present.

The most significant climate processes since the middle to late Pliocene (approximately 3 million years ago) are the glacial and interglacial cycles. The present interglacial period (the Holocene) has lasted about 11,700 years. Shaped by orbital variations, responses such as the rise and fall of continental ice sheets and significant sea-level changes helped create the climate. Other changes, including Heinrich events, Dansgaard–Oeschger events and the Younger Dryas, however, illustrate how glacial variations may also influence climate without the orbital forcing.

Glaciers leave behind moraines that contain a wealth of material—including organic matter, quartz, and potassium that may be dated—recording the periods in which a glacier advanced and retreated. Similarly, by tephrochronological techniques, the lack of glacier cover can be identified by the presence of soil or volcanic tephra horizons whose date of deposit may also be ascertained.

Vegetation



This image summarizes how climate change, associated with increased carbon dioxide levels, has affected plant growth.

A change in the type, distribution and coverage of vegetation may occur given a change in the climate. Some changes in climate may result in increased precipitation and warmth, resulting in improved plant growth and the subsequent sequestration of airborne CO₂. Larger, faster or more radical changes, however, may result in vegetation stress, rapid plant loss and desertification in certain circumstances. An example of this occurred during the Carboniferous Rainforest Collapse (CRC), an extinction event 300 million years ago. At this time vast rainforests covered the equatorial region of Europe and America. Climate change devastated these tropical rainforests, abruptly fragmenting the habitat into isolated 'islands' and causing the extinction of many plant and animal species.

Ice cores

Analysis of ice in a core drilled from a ice sheet such as the Antarctic ice sheet, can be used to show a link between temperature and global sea level variations. The air trapped in bubbles in the ice can also reveal the CO₂ variations of the atmosphere from the distant past, well before modern environmental influences. The study of these ice cores has been a significant indicator of the changes in CO₂ over many millennia, and continues to provide valuable information about the differences between ancient and modern atmospheric conditions.

Dendroclimatology

Dendroclimatology is the analysis of tree ring growth patterns to determine past climate variations. Wide and thick rings indicate a fertile, well-watered growing period, whilst thin, narrow rings indicate a time of lower rainfall and less-than-ideal growing conditions.

Pollen analysis

Palynology is the study of contemporary and fossil palynomorphs, including pollen. Palynology is used to infer the geographical distribution of plant species, which vary under different climate conditions. Different groups of plants have pollen with distinctive

shapes and surface textures, and since the outer surface of pollen is composed of a very resilient material, they resist decay. Changes in the type of pollen found in different layers of sediment in lakes, bogs, or river deltas indicate changes in plant communities. These changes are often a sign of a changing climate. As an example, palynological studies have been used to track changing vegetation patterns throughout the Quaternary glaciations and especially since the last glacial maximum.

Insects

Remains of beetles are common in freshwater and land sediments. Different species of beetles tend to be found under different climatic conditions. Given the extensive lineage of beetles whose genetic makeup has not altered significantly over the millennia, knowledge of the present climatic range of the different species, and the age of the sediments in which remains are found, past climatic conditions may be inferred.

Sea level change

Global sea level change for much of the last century has generally been estimated using tide gauge measurements collated over long periods of time to give a long-term average. More recently, altimeter measurements — in combination with accurately determined satellite orbits — have provided an improved measurement of global sea level change. To measure sea levels prior to instrumental measurements, scientists have dated coral reefs that grow near the surface of the ocean, coastal sediments, marine terraces, ooids in limestones, and nearshore archaeological remains. The predominant dating methods used are uranium series and radiocarbon, with cosmogenic radionuclides being sometimes used to date terraces that have experienced relative sea level fall.

Chapter-6

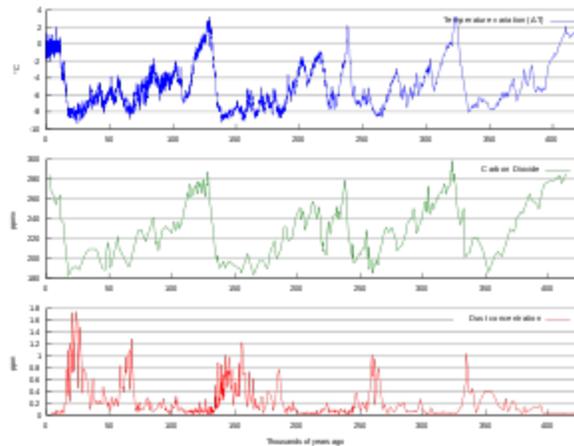
Ice Age



An artist's impression of ice age Earth at glacial maximum. Based on: "Ice age terrestrial carbon changes revisited" by Thomas J. Crowley (Global Biogeochemical Cycles, Vol. 9, 1995, pp. 377-389)



The Antarctic ice sheet. Ice sheets expand during an ice age.



Variations in temperature, CO₂, and dust from the Vostok ice core over the last 400,000 years

An **"ice age"** or, more precisely, **"glacial age"** is a generic geological period of long-term reduction in the temperature of the Earth's surface and atmosphere, resulting in the presence or expansion of continental ice sheets, polar ice sheets and alpine glaciers. Within a long-term ice age, individual pulses of extra cold climate are termed "glacial periods" (or alternatively "glacials" or "glaciations" or colloquially as "Ice Age"), and intermittent warm periods are called "interglacials". Glaciologically, *ice age* implies the presence of extensive ice sheets in the northern and southern hemispheres; by this definition we are still in the ice age that began at the start of the Pleistocene (because the Greenland and Antarctic ice sheets still exist).

More colloquially, "the ice age" refers to the most recent colder period that peaked at the Last Glacial Maximum approximately 20,000 years ago, in which extensive ice sheets lay over large parts of the North American and Eurasian continents.

Origin of ice age theory

In 1742 Pierre Martel (1706–1767), an engineer and geographer living in Geneva, visited the valley of Chamonix in the Alps of Savoy. Two years later he published an account of his journey. He reported that the inhabitants of that valley attributed the dispersal of erratic boulders to the fact that the glaciers had once extended much farther. Later similar explanations were reported from other regions of the Alps. In 1815 the carpenter and chamois hunter Jean-Pierre Perraudin (1767–1858) explained erratic boulders in the Val de Bagnes in the Swiss canton of Valais as being due to glaciers previously extending further. An unknown woodcutter from Meiringen in the Bernese Oberland advocated a similar idea in a discussion with the Swiss-German geologist Jean de Charpentier (1786–1855) in 1834. Comparable explanations are also known from the Val de Ferret in the Valais and the Seeland in western Switzerland and in Goethe's Scientific Work. Such explanations could also be found in other parts of the world. When the Bavarian naturalist Ernst von Bibra (1806–1878) visited the Chilean Andes in 1849–1850 the natives attributed fossil moraines to the former action of glaciers.

Meanwhile, European scholars had begun to wonder what had caused the dispersal of erratic material. From the middle of the 18th century some discussed ice as a means of transport. The Swedish mining expert Daniel Tilas (1712–1772) was, in 1742, the first person to suggest drifting sea ice in order to explain the presence of erratic boulders in the Scandinavian and Baltic regions. In 1795, the Scottish philosopher and gentleman naturalist, James Hutton (1726–1797), explained erratic boulders in the Alps with the action of glaciers. Two decades later, in 1818, the Swedish botanist Göran Wahlenberg (1780–1851) published his theory of a glaciation of the Scandinavian peninsula. He regarded glaciation as a regional phenomenon. Only a few years later, the Danish-Norwegian Geologist Jens Esmark (1763–1839) argued a sequence of worldwide ice ages. In a paper published in 1824, Esmark proposed changes in climate as the cause of those glaciations. He attempted to show that they originated from changes in the Earth's orbit. During the following years, Esmark's ideas were discussed and taken over in parts by Swedish, Scottish and German scientists. At the University of Edinburgh Robert Jameson (1774–1854) seemed to be relatively open towards Esmark's ideas. Jameson's remarks about ancient glaciers in Scotland were most probably prompted by Esmark. In Germany, Albrecht Reinhard Bernhardt (1797–1849), professor of forestry at Dreissigacker, adopted Esmark's theory. In a paper published in 1832, Bernhardt speculated about former polar ice caps reaching as far as the temperate zones of the globe.

Independently of these debates, the Swiss civil engineer Ignaz Venetz (1788–1859) in 1829, explained the dispersal of erratic boulders in the Alps, the nearby Jura Mountains and the North German Plain as being due to huge glaciers. When he read his paper before the Schweizerische Naturforschende Gesellschaft, most scientists remained sceptical. Finally, Venetz managed to convince his friend Jean de Charpentier. De Charpentier transformed Venetz's idea into a theory with a glaciation limited to the Alps. His thoughts resembled Wahlenberg's theory. In fact, both men shared the same volcanistic, or in de Charpentier's case rather plutonic assumptions, about earth history. In 1834, de

Charpentier presented his paper before the Schweizerische Naturforschende Gesellschaft. In the meantime, the German botanist Karl Friedrich Schimper (1803–1867) was studying mosses which were growing on erratic boulders in the alpine upland of Bavaria. He began to wonder where such masses of stone had come from. During the summer of 1835 he made some excursions to the Bavarian Alps. Schimper came to the conclusion that ice must have been the means of transport for the boulders in the alpine upland. In the winter of 1835 to 1836 he held some lectures in Munich. Schimper then assumed that there must have been global times of obliteration (“Verödungszeiten“) with a cold climate and frozen water. Schimper spent the summer months of 1836 at Devens, near Bex, in the Swiss Alps with his former university friend Louis Agassiz (1801–1873) and Jean de Charpentier. Schimper, de Charpentier and possibly Venetz convinced Agassiz that there had been a time of glaciation. During Winter 1836/7 Agassiz and Schimper developed the theory of a sequence of glaciations. They mainly drew upon the preceding works of Goethe, of Venetz, of de Charpentier and on their own fieldwork. There are indications that Agassiz was already familiar with Bernhardt's paper at that time. At the beginning of 1837 Schimper coined the term ice age (“Eiszeit“). In July 1837 Agassiz presented their synthesis before the annual meeting of the Schweizerische Naturforschende Gesellschaft at Neuchâtel. The audience was very critical or even opposed the new theory because it contradicted the established opinions on climatic history. Most contemporary scientist thought that the earth had been gradually cooling down since its birth as a molten globe.

In order to overcome this rejection, Agassiz embarked on geological fieldwork. He published his book *Study on glaciers* (“Études sur les glaciers“) in 1840. De Charpentier was put out by this as he had also been preparing a book about the glaciation of the Alps. De Charpentier felt that Agassiz should have given him precedence as it was he who had introduced Agassiz to in depth glacial research. Besides that, Agassiz had, as a result of personal quarrels, omitted any mention of Schimper in his book.

Altogether, it took several decades until the ice age theory was fully accepted. This happened on an international scale in the second half of the 1870s following the work of James Croll including the publication of *Climate and Time, in Their Geological Relations* in 1875 which provided a credible explanation for the causes of ice ages.

Evidence for ice ages

There are three main types of evidence for ice ages: geological, chemical, and paleontological.

Geological evidence for ice ages comes in various forms, including rock scouring and scratching, glacial moraines, drumlins, valley cutting, and the deposition of till or tillites and glacial erratics. Successive glaciations tend to distort and erase the geological evidence, making it difficult to interpret. Furthermore, this evidence was difficult to date exactly; early theories assumed that the glacials were short compared to the long interglacials. The advent of sediment and ice cores revealed the true situation: glacials are long, interglacials short. It took some time for the current theory to be worked out.

The **chemical** evidence mainly consists of variations in the ratios of isotopes in fossils present in sediments and sedimentary rocks and ocean sediment cores. For the most recent glacial periods ice cores provide climate proxies from their ice, and atmospheric samples from included bubbles of air. Because water containing heavier isotopes has a higher heat of evaporation, its proportion decreases with colder conditions. This allows a temperature record to be constructed. However, this evidence can be confounded by other factors recorded by isotope ratios.

The **paleontological** evidence consists of changes in the geographical distribution of fossils. During a glacial period cold-adapted organisms spread into lower latitudes, and organisms that prefer warmer conditions become extinct or are squeezed into lower latitudes. This evidence is also difficult to interpret because it requires (1) sequences of sediments covering a long period of time, over a wide range of latitudes and which are easily correlated; (2) ancient organisms which survive for several million years without change and whose temperature preferences are easily diagnosed; and (3) the finding of the relevant fossils.

Despite the difficulties, analyses of ice core and ocean sediment cores has shown periods of glacials and interglacials over the past few million years. These also confirm the linkage between ice ages and continental crust phenomena such as glacial moraines, drumlins, and glacial erratics. Hence the continental crust phenomena are accepted as good evidence of earlier ice ages when they are found in layers created much earlier than the time range for which ice cores and ocean sediment cores are available.

Major ice ages



Ice age map of northern central Europe. Red: maximum limit of Weichselian ice age; yellow: Saale ice age at maximum (Drenthe stage); blue: Elster ice age maximum glaciation.

There have been at least five major ice ages in the Earth's past. Outside these ages, the Earth seems to have been ice-free even in high latitudes.

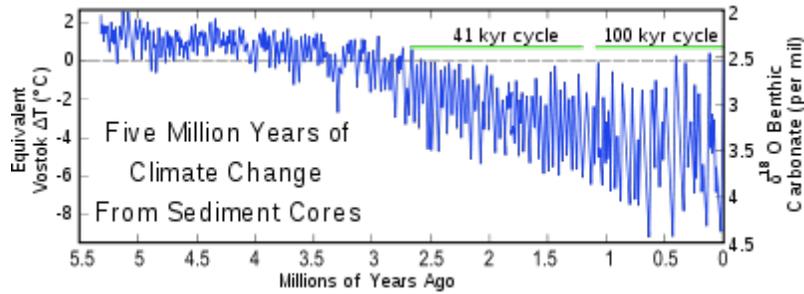
Rocks from the earliest well established ice age, called the Huronian, formed around 2.4 to 2.1 Ga (billion years) ago during the early Proterozoic Eon. Several hundreds of km of the Huronian Supergroup are exposed 10–100 km north the North Shore of Lake Huron extending from near Sault Ste. Marie to Sudbury NE of Lake Huron, with giant layers of now-lithified till beds, dropstones, varves, outwash, and scoured basement rocks. Correlative Huronian deposits have been found near Marquette, Michigan and correlation has been made with Paleoproterozoic glacial deposits from Western Australia.

The next well-documented ice age, and probably the most severe of the last billion years, occurred from 850 to 630 million years ago (the Cryogenian period) and may have produced a Snowball Earth in which glacial ice sheets reached the equator, possibly being ended by the accumulation of greenhouse gases such as CO₂ produced by volcanoes. "The presence of ice on the continents and pack ice on the oceans would inhibit both silicate weathering and photosynthesis, which are the two major sinks for CO₂ at present." It has been suggested that the end of this ice age was responsible for the subsequent Ediacaran and Cambrian Explosion, though this model is recent and controversial.

A minor ice age, the Andean-Saharan, occurred from 460 to 430 million years ago, during the Late Ordovician and the Silurian period. There were extensive polar ice caps at intervals from 350 to 260 million years ago in South Africa during the Carboniferous and early Permian Periods, associated with the Karoo Ice Age. Correlatives are known from Argentina, also forming in the center of the ancient supercontinent Gondwanaland.

The Karoo Ice Age occurred from 360 to 260 million years ago. It is named after the glacial tills found in the Karoo region of South Africa where evidence for this ice age was first clearly identified. It is thought that this ice age was largely caused by the evolution of land plants with the onset of the Devonian period. The Earth during this time was covered with an immense degree of vegetation compared to earlier times, and this caused a long term increase in planetary oxygen levels and reduction of CO₂ levels that resulted in this ice age.

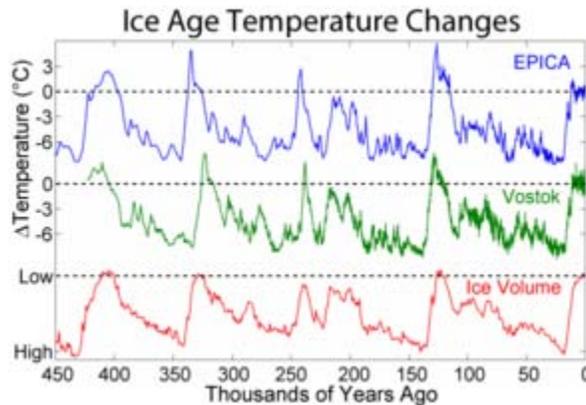
An ice sheet on Antarctica began to grow some 20 million years ago. The current ice age, the Pliocene-Quaternary glaciation, started about 2.58 million years ago during the late Pliocene when the spread of ice sheets in the Northern Hemisphere began. Since then, the world has seen cycles of glaciation with ice sheets advancing and retreating on 40,000- and 100,000-year time scales called glacial periods, glacials or glacial advances, and interglacial periods, interglacials or glacial retreats. The earth is currently in an interglacial, and the last glacial period ended about 10,000 years ago. All that remains of the continental ice sheets are the Greenland, Antarctic ice sheets and smaller glaciers such as on Baffin Island.



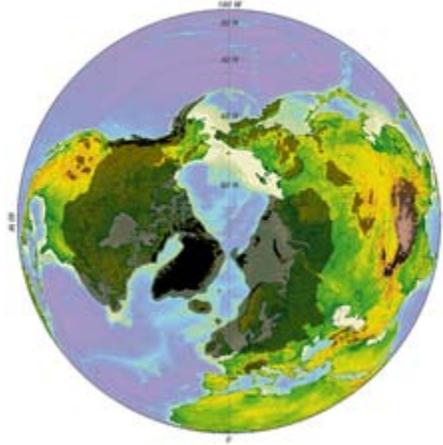
Sediment records showing the fluctuating sequences of glacials and interglacials during the last several million years.

Ice ages can be further divided by location and time; for example, the names *Riss* (180,000–130,000 years bp) and *Würm* (70,000–10,000 years bp) refer specifically to glaciation in the Alpine region. Note that the maximum extent of the ice is not maintained for the full interval. Unfortunately, the scouring action of each glaciation tends to remove most of the evidence of prior ice sheets almost completely, except in regions where the later sheet does not achieve full coverage.

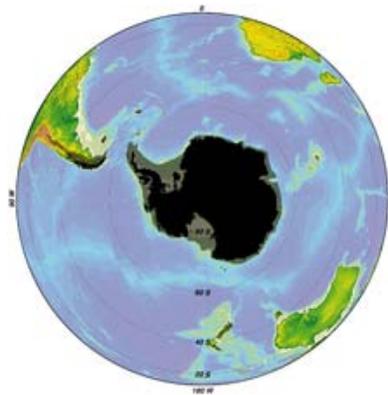
Glacials and interglacials



Shows the pattern of temperature and ice volume changes associated with recent glacials and interglacials



Minimum (interglacial, black) and maximum (glacial, grey) glaciation of the northern hemisphere



Minimum (interglacial, black) and maximum (glacial, grey) glaciation of the southern hemisphere

Within the ice ages (or at least within the current one), more temperate and more severe periods occur. The colder periods are called *glacial periods*, the warmer periods *interglacials*, such as the Eemian Stage.

Glacials are characterized by cooler and drier climates over most of the Earth and large land and sea ice masses extending outward from the poles. Mountain glaciers in otherwise unglaciated areas extend to lower elevations due to a lower snow line. Sea levels drop due to the removal of large volumes of water above sea level in the icecaps. There is evidence that ocean circulation patterns are disrupted by glaciations. Since the Earth has significant continental glaciation in the Arctic and Antarctic, we are currently in a glacial minimum of a glacial. Such a period between glacial maxima is known as an *interglacial*.

The Earth has been in an interglacial period known as the Holocene for more than 11,000 years. It was conventional wisdom that "the typical interglacial period lasts about 12,000 years," but this has been called into question recently. For example, an article in *Nature* argues that the current interglacial might be most analogous to a previous interglacial that

lasted 28,000 years. Predicted changes in orbital forcing suggest that the next glacial period would begin at least 50,000 years from now, even in absence of human-made global warming. Moreover, anthropogenic forcing from increased greenhouse gases might outweigh orbital forcing for as long as intensive use of fossil fuels continues. At a meeting of the American Geophysical Union (December 17, 2008), scientists detailed evidence in support of the controversial idea that the introduction of large-scale rice agriculture in Asia, coupled with extensive deforestation in Europe began to alter world climate by pumping significant amounts of greenhouse gases into the atmosphere over the last 1,000 years. In turn, a warmer atmosphere heated the oceans making them much less efficient storehouses of carbon dioxide and reinforcing global warming, possibly forestalling the onset of a new glacial age.

Positive and negative feedbacks in glacial periods

Each glacial period is subject to positive feedback which makes it more severe and negative feedback which mitigates and (in all cases so far) eventually ends it.

Positive feedback processes

Ice and snow increase the Earth's albedo, i.e. they make it reflect more of the sun's energy and absorb less. Hence, when the air temperature decreases, ice and snow fields grow, and this continues until competition with a negative feedback mechanism forces the system to an equilibrium. Also, the reduction in forests caused by the ice's expansion increases albedo.

Another theory proposed by Ewing and Donn in 1956 hypothesized that an ice-free Arctic Ocean leads to increased snowfall at high latitudes. When low-temperature ice covers the Arctic Ocean there is little evaporation or sublimation and the polar regions are quite dry in terms of precipitation, comparable to the amount found in mid-latitude deserts. This low precipitation allows high-latitude snowfalls to melt during the summer. An ice-free Arctic Ocean absorbs solar radiation during the long summer days, and evaporates more water into the Arctic atmosphere. With higher precipitation, portions of this snow may not melt during the summer and so glacial ice can form at lower altitudes *and* more southerly latitudes, reducing the temperatures over land by increased albedo as noted above. Furthermore, under this hypothesis the lack of oceanic pack ice allows increased exchange of waters between the Arctic and the North Atlantic Oceans, warming the Arctic and cooling the North Atlantic. (Current projected consequences of global warming include a largely ice-free Arctic Ocean within 5–20 years.) Additional fresh water flowing into the North Atlantic during a warming cycle may also reduce the global ocean water circulation. Such a reduction (by reducing the effects of the Gulf Stream) would have a cooling effect on northern Europe, which in turn would lead to increased low-latitude snow retention during the summer. It has also been suggested that during an extensive ice age glaciers may move through the Gulf of Saint Lawrence, extending into the North Atlantic ocean to an extent that the Gulf Stream is blocked.

Negative feedback processes

Ice sheets that form during glaciations cause erosion of the land beneath them. After some time, this will reduce land above sea level and thus diminish the amount of space on which ice sheets can form. This mitigates the albedo feedback, as does the lowering in sea level that accompanies the formation of ice sheets.

Another factor is the increased aridity occurring with glacial maxima, which reduces the precipitation available to maintain glaciation. The glacial retreat induced by this or any other process can be amplified by similar inverse positive feedbacks as for glacial advances.

Causes of ice ages

The causes of ice ages are not fully understood for both the large-scale ice age periods and the smaller ebb and flow of glacial–interglacial periods within an ice age. The consensus is that several factors are important: atmospheric composition (the concentrations of carbon dioxide, methane). The specific levels of the previously mentioned gases are now able to be seen with the new ice core samples from the Antarctic shelf over the past 650,000 years; changes in the Earth's orbit around the Sun known as Milankovitch cycles (and possibly the Sun's orbit around the galaxy); the motion of tectonic plates resulting in changes in the relative location and amount of continental and oceanic crust on the Earth's surface, which affect wind and ocean currents; variations in solar output; the orbital dynamics of the Earth-Moon system; and the impact of relatively large meteorites, and volcanism including eruptions of supervolcanoes.

Some of these factors influence each other. For example, changes in Earth's atmospheric composition (especially the concentrations of greenhouse gases) may alter the climate, while climate change itself can change the atmospheric composition (for example by changing the rate at which weathering removes CO₂).

Maureen Raymo, William Ruddiman and others propose that the Tibetan and Colorado Plateaus are immense CO₂ "scrubbers" with a capacity to remove enough CO₂ from the global atmosphere to be a significant causal factor of the 40 million year Cenozoic Cooling trend. They further claim that approximately half of their uplift (and CO₂ "scrubbing" capacity) occurred in the past 10 million years.

Changes in Earth's atmosphere

There is evidence that greenhouse gas levels fell at the start of ice ages and rose during the retreat of the ice sheets, but it is difficult to establish cause and effect. Greenhouse gas levels may also have been affected by other factors which have been proposed as causes of ice ages, such as the movement of continents and volcanism.

The Snowball Earth hypothesis maintains that the severe freezing in the late Proterozoic was ended by an increase in CO₂ levels in the atmosphere, and some supporters of Snowball Earth argue that it was caused by a reduction in atmospheric CO₂. The hypothesis also warns of future Snowball Earths.

The August 2009 edition of *Science* provides further evidence that changes in solar insolation provide the initial trigger for the Earth to warm after an Ice Age, with secondary factors like increases in greenhouse gases accounting for the magnitude of the change.

William Ruddiman has proposed the early anthropocene hypothesis, according to which the anthropocene era, as some people call the most recent period in the Earth's history when the activities of the human species first began to have a significant global impact on the Earth's climate and ecosystems, did not begin in the 18th century with the advent of the Industrial Era, but dates back to 8,000 years ago, due to intense farming activities of our early agrarian ancestors. It was at that time that atmospheric greenhouse gas concentrations stopped following the periodic pattern of the Milankovitch cycles. In his overdue-glaciation hypothesis Ruddiman states that an incipient ice age would probably have begun several thousand years ago, but the arrival of that scheduled ice age was forestalled by the activities of early farmers.

Position of the continents

The geological record appears to show that ice ages start when the continents are in positions which block or reduce the flow of warm water from the equator to the poles and thus allow ice sheets to form. The ice sheets increase the Earth's reflectivity and thus reduce the absorption of solar radiation. With less radiation absorbed the atmosphere cools; the cooling allows the ice sheets to grow, which further increases reflectivity in a positive feedback loop. The ice age continues until the reduction in weathering causes an increase in the greenhouse effect.

There are three known configurations of the continents which block or reduce the flow of warm water from the equator to the poles:

- A continent sits on top of a pole, as Antarctica does today.
- A polar sea is almost land-locked, as the Arctic Ocean is today.
- A supercontinent covers most of the equator, as Rodinia did during the Cryogenian period.

Since today's Earth has a continent over the South Pole and an almost land-locked ocean over the North Pole, geologists believe that Earth will continue to endure glacial periods in the geologically near future.

Some scientists believe that the Himalayas are a major factor in the current ice age, because these mountains have increased Earth's total rainfall and therefore the rate at which CO₂ is washed out of the atmosphere, decreasing the greenhouse effect. The

Himalayas' formation started about 70 million years ago when the Indo-Australian Plate collided with the Eurasian Plate, and the Himalayas are still rising by about 5 mm per year because the Indo-Australian plate is still moving at 67 mm/year. The history of the Himalayas broadly fits the long-term decrease in Earth's average temperature since the mid-Eocene, 40 million years ago.

Fluctuations in ocean currents

Another important contribution to ancient climate regimes is the variation of **ocean currents**, which are modified by continent position, sea levels and salinity, as well as other factors. They have the ability to cool (e.g. aiding the creation of Antarctic ice) and the ability to warm (e.g. giving the British Isles a temperate as opposed to a boreal climate). The closing of the Isthmus of Panama about 3 million years ago may have ushered in the present period of strong glaciation over North America by ending the exchange of water between the tropical Atlantic and Pacific Oceans.

Analyses suggest that ocean current fluctuations can adequately account for recent glacial oscillations. During the last glacial period the sea-level has fluctuated 20–30 m as water was sequestered, primarily in the northern hemisphere ice sheets. When ice collected and the sea level dropped sufficiently, flow through the Bering Strait (the narrow strait between Siberia and Alaska is ~50 m deep today) was reduced, resulting in increased flow from the North Atlantic. This realigned the thermohaline circulation in the Atlantic, increasing heat transport into the Arctic, which melted the polar ice accumulation and reduced other continental ice sheets. The release of water raised sea levels again, restoring the ingress of colder water from the Pacific with an accompanying shift to northern hemisphere ice accumulation.

Uplift of the Tibetan plateau and surrounding mountain areas above the snowline

Matthias Kuhle's geological theory of Ice Age development was suggested by the existence of an ice sheet covering the Tibetan plateau during the Ice Ages (Last Glacial Maximum?). According to Kuhle, the plate-tectonic uplift of Tibet past the snow-line has led to a c. 2.4 million km² ice surface with a 70% greater albedo than the bare land surface. The reflection of energy into space resulted in a global cooling, triggering the Pleistocene Ice Age. Because this highland is at a subtropical latitude, with 4 to 5 times the insolation of high-latitude areas, what would be Earth's strongest heating surface has turned into a cooling surface.

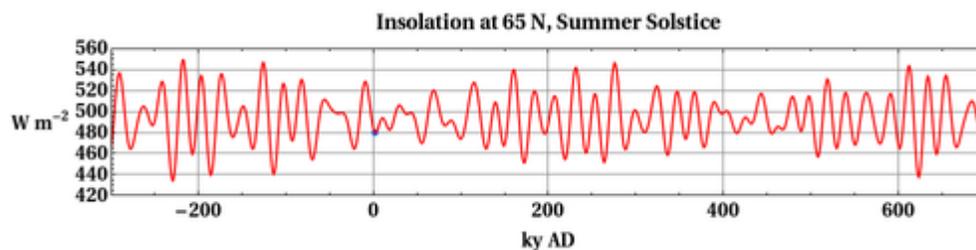
Kuhle explains the interglacial periods by the 100 000-year cycle of radiation changes due to variations of the Earth's orbit. This comparatively insignificant warming, when combined with the lowering of the Nordic inland ice areas and Tibet due to the weight of the superimposed ice-load, has led to the repeated complete thawing of the inland ice areas.

Variations in Earth's orbit (Milankovitch cycles)

The Milankovitch cycles are a set of cyclic variations in characteristics of the Earth's orbit around the Sun. Each cycle has a different length, so at some times their effects reinforce each other and at other times they (partially) cancel each other.

It is very unlikely that the Milankovitch cycles can start or end an ice age (series of glacial periods):

- Even when their effects reinforce each other they are not strong enough.
- The "peaks" (effects reinforce each other) and "troughs" (effects cancel each other) are much more regular and much more frequent than the observed ice ages.



Past and future of daily average insolation at top of the atmosphere on the day of the summer solstice, at 65 N latitude.

In contrast, there is strong evidence that the Milankovitch cycles affect the occurrence of glacial and interglacial periods within an ice age. The present ice ages are the most studied and best understood, particularly the last 400,000 years, since this is the period covered by ice cores that record atmospheric composition and proxies for temperature and ice volume. Within this period, the match of glacial/interglacial frequencies to the Milanković orbital forcing periods is so close that orbital forcing is generally accepted. The combined effects of the changing distance to the Sun, the precession of the Earth's axis, and the changing tilt of the Earth's axis redistribute the sunlight received by the Earth. Of particular importance are changes in the tilt of the Earth's axis, which affect the intensity of seasons. For example, the amount of solar influx in July at 65 degrees north latitude varies by as much as 25% (from 450 W/m^2 to 550 W/m^2). It is widely believed that ice sheets advance when summers become too cool to melt all of the accumulated snowfall from the previous winter. Some workers believe that the strength of the orbital forcing is too small to trigger glaciations, but feedback mechanisms like CO_2 may explain this mismatch.

While Milankovitch forcing predicts that cyclic changes in the Earth's orbital elements can be expressed in the glaciation record, additional explanations are necessary to explain which cycles are observed to be most important in the timing of glacial–interglacial periods. In particular, during the last 800,000 years, the dominant period of glacial–interglacial oscillation has been 100,000 years, which corresponds to changes in Earth's orbital eccentricity and orbital inclination. Yet this is by far the weakest of the three frequencies predicted by Milankovitch. During the period 3.0–0.8 million years ago, the

dominant pattern of glaciation corresponded to the 41,000-year period of changes in Earth's obliquity (tilt of the axis). The reasons for dominance of one frequency versus another are poorly understood and an active area of current research, but the answer probably relates to some form of resonance in the Earth's climate system.

The "traditional" Milankovitch explanation struggles to explain the dominance of the 100,000-year cycle over the last 8 cycles. Richard A. Muller and Gordon J. MacDonald and others have pointed out that those calculations are for a two-dimensional orbit of Earth but the three-dimensional orbit also has a 100,000-year cycle of orbital inclination. They proposed that these variations in orbital inclination lead to variations in insolation, as the Earth moves in and out of known dust bands in the solar system. Although this is a different mechanism to the traditional view, the "predicted" periods over the last 400,000 years are nearly the same. The Muller and MacDonald theory, in turn, has been challenged by Jose Antonio Rial.

Another worker, William Ruddiman, has suggested a model that explains the 100,000-year cycle by the modulating effect of eccentricity (weak 100,000-year cycle) on precession (26,000-year cycle) combined with greenhouse gas feedbacks in the 41,000- and 26,000-year cycles. Yet another theory has been advanced by Peter Huybers who argued that the 41,000-year cycle has always been dominant, but that the Earth has entered a mode of climate behavior where only the second or third cycle triggers an ice age. This would imply that the 100,000-year periodicity is really an illusion created by averaging together cycles lasting 80,000 and 120,000 years (Nature 434, 2005,). This theory is consistent with a simple empirical multi-state model proposed by Didier Paillard. Paillard suggests that the late Pleistocene glacial cycles can be seen as jumps between three quasi-stable climate states. The jumps are induced by the orbital forcing, while in the early Pleistocene the 41,000-year glacial cycles resulted from jumps between only two climate states. A dynamical model explaining this behavior was proposed by Peter Ditlevsen. This is in support of the suggestion that the late Pleistocene glacial cycles are not due to the weak 100,000-year eccentricity cycle, but a non-linear response to mainly the 41,000-year obliquity cycle.

Variations in the Sun's energy output

There are at least two types of variation in the Sun's energy output:

- In the very long term, astrophysicists believe that the Sun's output increases by about 10% every one billion (10^9) years.
- Shorter-term variations such as sunspot cycles, and longer episodes such as the Maunder minimum, which occurred during the coldest part of the Little Ice Age.

The long-term increase in the Sun's output cannot be a cause of ice ages.

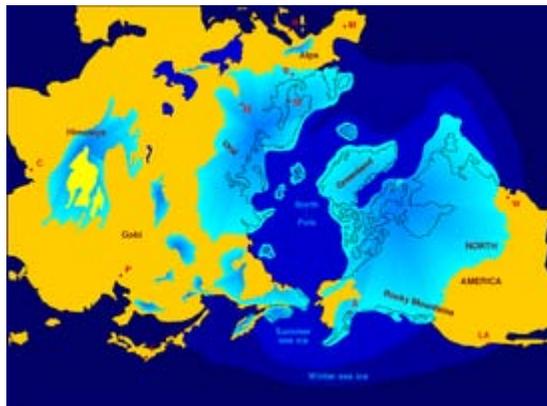
Volcanism

Volcanic eruptions may have contributed to the inception and/or the end of ice age periods. One suggested explanation of the Paleocene-Eocene Thermal Maximum is that undersea volcanoes released methane from clathrates and thus caused a large and rapid increase in the greenhouse effect. There appears to be no geological evidence for such eruptions at the right time, but this does not prove they did not happen.

Biological effects

There is a theory that about 15000 BC prehistoric man, by killing the mammoths, removed a major grazing factor and so let the North American and Eurasian tundra get overgrown with trees, which, sticking up above the winter snow, made the land darker and made the spring warming much quicker, and so ended the last Ice Age.

Recent glacial and interglacial phases



Northern hemisphere glaciation during the last ice ages. The set up of 3 to 4 km thick ice sheets caused a sea level lowering of about 120 m.

Glacial stages in North America

The major glacial stages of the current ice age in North America are the Illinoian, Sangamonian and Wisconsin stages. The use of the Nebraskan, Afton, Kansan, and Yarmouthian (Yarmouth) stages to subdivide the ice age in North America have been discontinued by Quaternary geologists and geomorphologists. These stages have all been merged into the Pre-Illinoian Stage in the 1980s.

During the most recent North American glaciation, during the latter part of the Wisconsin Stage (26,000 to 13,300 years ago), ice sheets extended to about 45 degrees north latitude. These sheets were 3 to 4 km thick.

This Wisconsin glaciation left widespread impacts on the North American landscape. The Great Lakes and the Finger Lakes were carved by ice deepening old valleys. Most of the lakes in Minnesota and Wisconsin were gouged out by glaciers and later filled with glacial meltwaters. The old Teays River drainage system was radically altered and largely reshaped into the Ohio River drainage system. Other rivers were dammed and diverted to new channels, such as the Niagara, which formed a dramatic waterfall and gorge, when the waterflow encountered a limestone escarpment. Another similar waterfall, at the present Clark Reservation State Park near Syracuse, New York, is now dry.

The area from Long Island to Nantucket was formed from glacial till, and the plethora of lakes on the Canadian Shield in northern Canada can be almost entirely attributed to the action of the ice. As the ice retreated and the rock dust dried, winds carried the material hundreds of miles, forming beds of loess many dozens of feet thick in the Missouri Valley. Isostatic rebound continues to reshape the Great Lakes and other areas formerly under the weight of the ice sheets.

The Driftless Zone, a portion of western and southwestern Wisconsin along with parts of adjacent Minnesota, Iowa, and Illinois, was not covered by glaciers.

Effects of glaciation



Scandinavia exhibits some of the typical effects of ice age glaciation such as fjords and lakes.

Although the last glacial period ended more than 8,000 years ago, its effects can still be felt today. For example, the moving ice carved out the landscape in Canada, Greenland, northern Eurasia and Antarctica. The erratic boulders, till, drumlins, eskers, fjords, kettle lakes, moraines, cirques, horns, etc., are typical features left behind by the glaciers.

The weight of the ice sheets was so great that they deformed the Earth's crust and mantle. After the ice sheets melted, the ice-covered land rebounded. Due to the high viscosity of the Earth, the flow of mantle rocks which controls the rebound process is very slow – at a rate of about 1 cm/year near the center of rebound today.

During glaciation, water was taken from the oceans to form the ice at high latitudes, thus global sea level dropped by about 110 meters, exposing the continental shelves and forming land-bridges between land-masses for animals to migrate. During deglaciation, the melted ice-water returned to the oceans, causing sea level to rise. This process can cause sudden shifts in coastlines and hydration systems resulting in newly submerged lands, emerging lands, collapsed ice dams resulting in salination of lakes, new ice dams creating vast areas of freshwater, and a general alteration in regional weather patterns on a large but temporary scale. It can even cause temporary reglaciation. This type of chaotic pattern of rapidly changing land, ice, saltwater and freshwater has been proposed as the likely model for the Baltic and Scandinavian regions, as well as much of central North America at the end of the last glacial maximum, with the present-day coastlines only being achieved in the last few millennia of prehistory. Also, the effect of elevation on Scandinavia submerged a vast continental plain that had existed under much of what is now the North Sea, connecting the British Isles to Continental Europe.

The redistribution of ice-water on the surface of the Earth and the flow of mantle rocks causes changes in the gravitational field as well as changes to the distribution of the moment of inertia of the Earth. These changes to the moment of inertia result in a change in the angular velocity, axis, and wobble of the Earth's rotation.

The weight of the redistributed surface mass loaded the lithosphere, caused it to flexure and also induced stress within the Earth. The presence of the glaciers generally suppressed the movement of faults below (Johnston 1989, Wu & Hasegawa 1996, Turpeinen et al. 2008). However, during deglaciation, the faults experience accelerated slip, and earthquakes are triggered. Earthquakes triggered near the ice margin may in turn accelerate ice calving and may account for the Heinrich events (Hunt & Malin 1998). As more ice is removed near the ice margin, more intraplate earthquakes are induced and this positive feedback may explain the fast collapse of ice sheets.

In Europe, glacial erosion and isostatic sinking from weight of ice made the Baltic Sea, which before the Ice Age was all land drained by a big river Eridanos.

Chapter-7

Supervolcano

A **supervolcano** is a volcano capable of producing a volcanic eruption with ejecta greater than 1,000 cubic kilometers (240 cubic miles). This is thousands of times larger than most historic volcanic eruptions. Supervolcanoes can occur when magma in the Earth rises into the crust from a hotspot but is unable to break through the crust. Pressure builds in a large and growing magma pool until the crust is unable to contain the pressure. They can also form at convergent plate boundaries (for example, Toba) and continental hotspot locations (for example, Yellowstone).

The Discovery Channel highlighted six known supervolcanoes: the Yellowstone, Long Valley, and Valles Caldera in the United States; Lake Toba, North Sumatra, Indonesia; Taupo Volcano, North Island, New Zealand; and Aira Caldera, Kagoshima Prefecture, Kyūshū, Japan. Although there are only a handful of Quaternary supervolcanoes, supervolcanic eruptions typically cover huge areas with lava and volcanic ash and cause a long-lasting change to weather (such as the triggering of a small ice age) sufficient to threaten the extinction of species.

Terminology

The term "supervolcano" was originally used in the BBC popular science television program *Horizon* in 2000 to refer to these types of eruptions. That program introduced the subject of large-scale volcanic eruptions to the general public.

Volcanologists and geologists do not refer to "supervolcanoes" in their scientific work, since this is a blanket term that can be applied to number of different geothermal conditions. Since 2003, however, the term has been used by professionals when presenting to the public. The term *megacaldera* is sometimes used for calderas with supervolcano characteristics, such as the Blake River Megacaldera Complex in the Abitibi greenstone belt of Ontario and Quebec, Canada. Eruptions that rate VEI 8 are termed "super eruptions".

Though there is no well-defined minimum explosive size for a "supervolcano", there are at least two types of volcanic eruption that have been identified as supervolcanoes: large igneous provinces and massive eruptions.

Large igneous provinces

Large Igneous provinces (LIP) are extremely large accumulations of igneous rocks—either intrusive, extrusive, or both—which are found in the earth's crust. In 1992 researchers (Coffin & Eldholm 1992) used the term 'large igneous province' to describe very large accumulations—areas greater than 100,000 square kilometers (slightly larger than the area of Portugal)—of mafic igneous rocks that were erupted or emplaced at depth within an extremely short geological time interval—a few million years or less. Mafic, basalt sea floors and other geological products of 'normal' plate tectonics were not included in the definition.

The definition of 'LIP' has been expanded and refined, and is still a work in progress. 'LIP' is now frequently used to also describe voluminous areas of, not just mafic, but all types of igneous rocks. Sub-categorization of LIP's into Large Volcanic Provinces (LVP) and Large Plutonic Provinces (LPP), and including rocks produced by 'normal' plate tectonic processes, has been proposed.

Mantle plumes, a recently apprehended and still poorly-understood and controversial geological process, are thought to be the source of many or all of the LIP's that are not associated with 'normal plate tectonics.'

Some LIP's are now intact, i.e. the basaltic Deccan Traps in India; others have been dismembered by plate tectonic motion, i.e. the basaltic Central Atlantic Magmatic Province (CAMP) parts of which are found in Brazil, the eastern United States and Canada, and northwestern Africa.

As originally defined LIPs include continental flood basalts, oceanic plateaus, large dike swarms (the eroded roots of a volcanic province), and volcanic rifted margins. Most of these LIPs consist of basalt, but some contain large volumes of associated rhyolite (e.g. the Columbia River Basalt Group in the western United States); the rhyolite is typically very dry compared to island arc rhyolites, with much higher eruption temperatures (850°C to 1000°C) than normal rhyolites. Some new definitions of the term 'LIP' include large granitic provinces such as those found in the Andes Mountains of South America and in western North America.

When created, LIPs often have an areal extent of a few million km² and volumes on the order of 1 million km³. In most cases, the majority of a basaltic LIP's volume is emplaced in less than 1 million years. One of the conundra of such LIPs origins is to understand how enormous volumes of basaltic magma are formed and erupted over such short time scales, with effusion rates up to an order of magnitude greater than mid-ocean ridge basalts.

Theories of formation

Large igneous provinces are often linked to active hotspots by linear chains of volcanic islands or volcanoes, leading to models that connect their origins to mantle plumes. In this hypothesis, mantle plumes consist of a bulbous head and a thin tail that feeds hot mantle into the head. When the rising plume head encounters the lithosphere, it spreads out and melts catastrophically to form large volumes of basalt magma in 1-2 million years. Subsequent volcanism originates with the plume tail. The movement of lithosphere across the surface of the Earth in response to plate tectonics causes the plume tail volcanics to form linear island chains. The impact of the plume on the base of continental lithosphere may cause rifting and breakup of the continent, creating conjugate LIPs on opposite sides of an ocean basin (e.g., the Parana-Etendeka pair of South America-Africa).

Alternate theories include delamination of eclogitic lower crust, edge effects of thick lithosphere, and meteorite impact.

Relationship of LIP's to extinction events

Eruptions or emplacements of LIP's appear to have, in some cases, occurred simultaneously with oceanic anoxic events and extinction events. The most important examples are the Deccan Traps (Cretaceous–Tertiary extinction event), the Karoo-Ferrar (Pliensbachian-Toarcian extinction), the Central Atlantic Magmatic Province (Triassic-Jurassic extinction event), and the Siberian traps (Permian-Triassic extinction event).

Several mechanisms are proposed to explain the association of LIP's with extinction events. The eruption of basaltic LIP's onto the earth's surface releases large volumes of sulfate gas, which forms sulfuric acid in the atmosphere; this absorbs heat and causes substantial cooling (e.g., the Laki eruption in Iceland, 1783). Oceanic LIP's can reduce oxygen in seawater by either direct oxidation reactions with metals in hydrothermal fluids or by causing algal blooms that consume large amounts of oxygen (Kerr 2005).

Examples of LIPs

These are well documented large igneous provinces in geological research.

- Ethiopian Highlands
- Columbia River Basalt Group
- Coppermine River Group (Canadian Shield)
- Deccan Traps (India)
- Equatorial Atlantic Magmatic Province (Maranhão, Brazil-Ghana)
- Paraná and Etendeka traps (Paraná, Brazil-NE Namibia)
- Brazilian Highlands

- Rio de la Plata Craton (Uruguay)
- Karoo-Ferrar (South Africa-Antarctica)
- Siberian Traps (Russia)
- Emeishan Traps (western China)

Oceanic Plateaus

- Wrangellia Terrane (Alaska and Canada)
- Caribbean large igneous province (Caribbean Sea)
- Kerguelen Plateau (Indian Ocean)
- Ontong Java Plateau, Manihiki Plateau and Hikurangi Plateau (southwest Pacific Ocean)
- Jameson Land

Volcanic Rifted Margins

- High Arctic Large Igneous Province (includes the Ellesmere Island Volcanics, Strand Fiord Formation, Alpha Ridge, Franz Josef Land and Svalbard.)
- North Atlantic Igneous Province (includes basalts in Greenland, Iceland, Ireland, Scotland, Faroes)
- Central Atlantic Magmatic Province (eastern United States and Canada, northern South America, northwest Africa)

Dike Swarms

- Mackenzie dike swarm (Canadian Shield)
- Long Range dikes (Newfoundland and Labrador, Canada)
- Mistassini dike swarm (western Quebec, Canada)
- Matachewan dike swarm (northern Ontario, Canada)
- Sorachi Plateau and Belt (Hokkaido, Japan)

Sills

- Winagami sill complex (northwestern Alberta, Canada)

Silicic LIPs

- Chon Aike (Argentina)
- Gawler (Australia)
- Sierra Madre Occidental

LIPs and Ore deposits

Large igneous provinces are associated with a handful of ore deposit types including:

- Ni-CU PGE's

- Porphyries
- Iron oxide copper gold (IOCG)
- Kimberlites

World's Largest Eruption



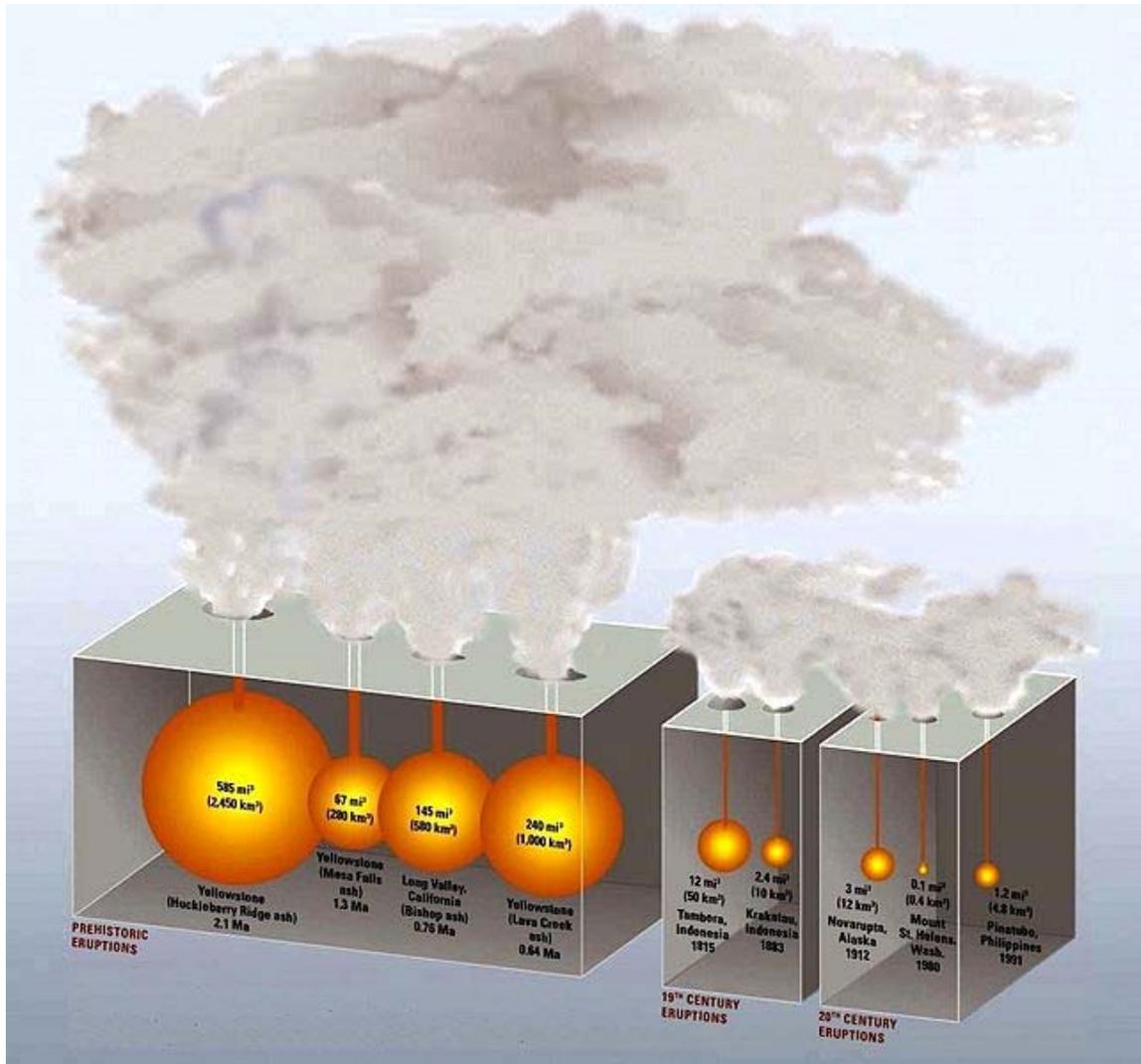
The 1991 eruption of Mount Pinatubo, the largest eruption since 1912, is dwarfed by the eruptions in this list

In a volcanic eruption, lava, tephra (volcanic bombs, lapilli, and ash), and various gases are expelled from a volcanic vent or fissure. While many eruptions only pose dangers to the immediately surrounding area, Earth's largest eruptions can have a major regional or even global impact, with some affecting the climate and contributing to mass extinctions. Volcanic eruptions can generally be characterized as either explosive eruptions, sudden ejections of rock and ash, or effusive eruptions, relatively gentle outpourings of lava. A separate list is given below for each type.

All of the eruptions listed below have produced at least 1,000 km³ (240 cu mi) of lava and tephra; for explosive eruptions, this corresponds to a Volcanic Explosivity Index (or VEI) of 8. They are at least a thousand times larger than the 1980 eruption of Mount St. Helens which produced only 1 km³ (0.2 cu mi) of material, and at least six times larger

than the 1815 eruption of Mount Tambora, the largest eruption in recent history, which produced 160 km³ (38 cu mi) of volcanic deposits.

There have probably been many such eruptions during Earth's history beyond those shown in these lists. However erosion and plate tectonics have taken their toll, and many eruptions have not left enough evidence for geologists to establish their size. Even for the eruptions listed here, estimates of the volume erupted can be subject to considerable uncertainty.



Comparison of four large VEI 7 and 8 eruptions (left) with major recent eruptions (right), including the 1980 eruption of Mount St. Helens (the smallest shown).

Explosive eruptions

In explosive eruptions, the eruption of magma is driven by the rapid release of pressure, often involving the explosion of gas previously dissolved within the material. The most

famous and destructive historical eruptions are mainly of this type. An eruptive phase can consist of a single eruption, or a sequence of several eruptions spread over several days, weeks or months. Explosive eruptions usually involve thick, highly viscous felsic magma, high in volatiles like water vapor and carbon dioxide. Pyroclastic materials are the primary product, typically in the form of tuff. Eruptions the size of that at Lake Toba 74 thousand years ago (2800 km³ or more) occur worldwide every 50,000 to 100,000 years.

Volcano— Eruption	Age (Ma)	Location	Volume (km³)	Notes
Guarapuava — Tamarana—Sarusas	132	Paraná and Etendeka traps	8,600	
Santa Maria—Fria	~132	Paraná and Etendeka traps	7,800	
Guarapuava — Ventura	~132	Paraná and Etendeka traps	7,600	
Sam Ignimbrite and Green Tuff	29.5	Yemen	6,800	Volume includes 5550 km ³ of distal tuffs. This estimate is uncertain to a factor of 2 or 3.
Goboboseb— Messum volcanic centre—Springbok quartz latite unit	132	Paraná and Etendeka traps, Brazil and Namibia	6,340	
Caxias do Sul— Grootberg	~132	Paraná and Etendeka traps	5,650	
La Garita Caldera— Fish Canyon tuff	27.8	San Juan volcanic field, Colorado	5,000	Commonly regarded as the largest tuff ever measured on Earth, or largest confidently- measured tuff on earth. It is part of at least 20 large caldera- forming eruptions in the San Juan volcanic field and surrounding area that formed around 26 to 35 Ma.
Jacui—Goboboseb II	~132	Paraná and Etendeka traps	4,350	
Ourinhos— Khoraseb	~132	Paraná and Etendeka traps	3,900	
Jabal Kura'a Ignimbrite	29.6	Yemen	3,800	Volume estimate is uncertain to a factor of 2 or 3.
Windows Butte tuff	31.4	William's Ridge, central Nevada	3,500	Part of the Mid-Tertiary ignimbrite flare-up
Anita Garibaldi—	~132	Paraná and	3,450	

Beacon		Etendeka traps		
Indian Peak Caldera Complex—Wah Wah Springs tuff	29.5	Eastern Nevada/Western Utah	3,200	Indian Peak Caldera Complex total volume over 10,000 cubic km, Wah Wah Springs tuff being the largest
Oxaya ignimbrites	19	Chile	3,000	Really a regional correlation of many ignimbrites originally thought to be distinct
Lund Tuff	29	Great Basin, USA	3,000	Similar in composition to the Fish Canyon Tuff
Lake Toba—Youngest Toba Tuff	0.073	Sunda Arc, Indonesia	2,800	Largest eruption on earth in at least the last 25 million years, responsible for the Toba catastrophe theory, a population bottleneck of the human species
Pacana Caldera—Atana ignimbrite	4	Chile	2,800	Forms a resurgent caldera.
Iftar Alkalb—Tephra 4 W	29.5	Afro-Arabian	2,700	
Yellowstone caldera—Huckleberry Ridge Tuff	2.059	Yellowstone hotspot	2,450	Largest Yellowstone eruption on record
Whakamaru	0.254	Taupo Volcanic Zone, New Zealand	2,000	Largest in the Southern Hemisphere in the Late Quaternary
Palmas BRA-21—Wereldsend	29.5	Paraná and Etendeka traps	1,900	
Kilgore tuff	4.3	Near Kilgore, Idaho	1,800	Last of the eruptions from the Heise volcanic field
Sana'a Ignimbrite—Tephra 2W63	29.5	Afro-Arabian	1,600	
Millbrig eruptions—Bentonites	454	England, exposed in Northern Europe and Eastern US	1,509	One of the oldest large eruptions preserved
Blacktail tuff	6.5	Blacktail, Idaho	1,500	First of several eruptions from the Heise volcanic field
Emory Caldera—Kneeling Nun tuff	33	Southwestern New Mexico	1,310	
Timber Mountain tuff	11.6	Southwestern Nevada	1,200	Also includes a 900 cubic km tuff as a second member in the tuff

Paintbrush tuff (Topopah Spring Member)	12.8	Southwestern Nevada	1,200	Related to a 1000 cubic km tuff (Tiva Canyon Member) as another member in the Paintbrush tuff
Bachelor— Carpenter Ridge tuff	28	San Juan volcanic field	1,200	Part of at least 20 large caldera- forming eruptions, including the world's largest, the Fish Canyon tuff in the San Juan volcanic field and surrounding area that formed around 26 to 35 Ma
Bursum—Apache Springs Tuff	28.5	Southern New Mexico	1,200	Related to a 1050 cubic km tuff, the Bloodgood Canyon tuff
Taupo Volcano— Oruanui eruption	0.027	Taupo volcanic zone, New Zealand	1,170	Most recent VEI 8 eruption
Huaylillas Ignimbrite	15	Bolivia	1,100	Predates half of the uplift of the central Andes
Bursum— Bloodgood Canyon tuff	28.5	Southern New Mexico	1,050	Related to a 1200 cubic km tuff, the Apache Springs tuff
Yellowstone Caldera—Lava Creek Tuff	0.639	Yellowstone hotspot	1,000	Last large eruption in the Yellowstone National Park area
Cerro Galán	2.2	Catamarca Province, Argentina	1,000	Elliptical caldera is ~35 km wide
Paintbrush tuff (Tiva Canyon Member)	12.7	Southwestern Nevada	1,000	Related to a 1200 cubic km tuff (Topopah Spring Member) as another member in the Paintbrush tuff
San Juan—Sapinero Mesa Tuff	28	San Juan volcanic field	1,000	Part of at least 20 large caldera- forming eruptions, including the world's largest, the Fish Canyon tuff in the San Juan volcanic field and surrounding area that formed around 26 to 35 Ma
Uncompahgre— Dillon & Sapinero Mesa Tuffs	28.1	San Juan volcanic field	1,000	Part of at least 20 large caldera- forming eruptions, including the world's largest, the Fish Canyon tuff in the San Juan volcanic field and surrounding area that formed around 26 to

				35 Ma
Platoro—Chiquito Peak tuff	28.2	San Juan volcanic field	1,000	Part of at least 20 large caldera-forming eruptions, including the world's largest, the Fish Canyon tuff in the San Juan volcanic field and surrounding area that formed around 26 to 35 Ma
Mount Princeton—Wall Mountain tuff	35.3	Thirtynine Mile volcanic area, Colorado	1,000	Helped cause the exceptional preservation at Florissant Fossil Beds National Monument

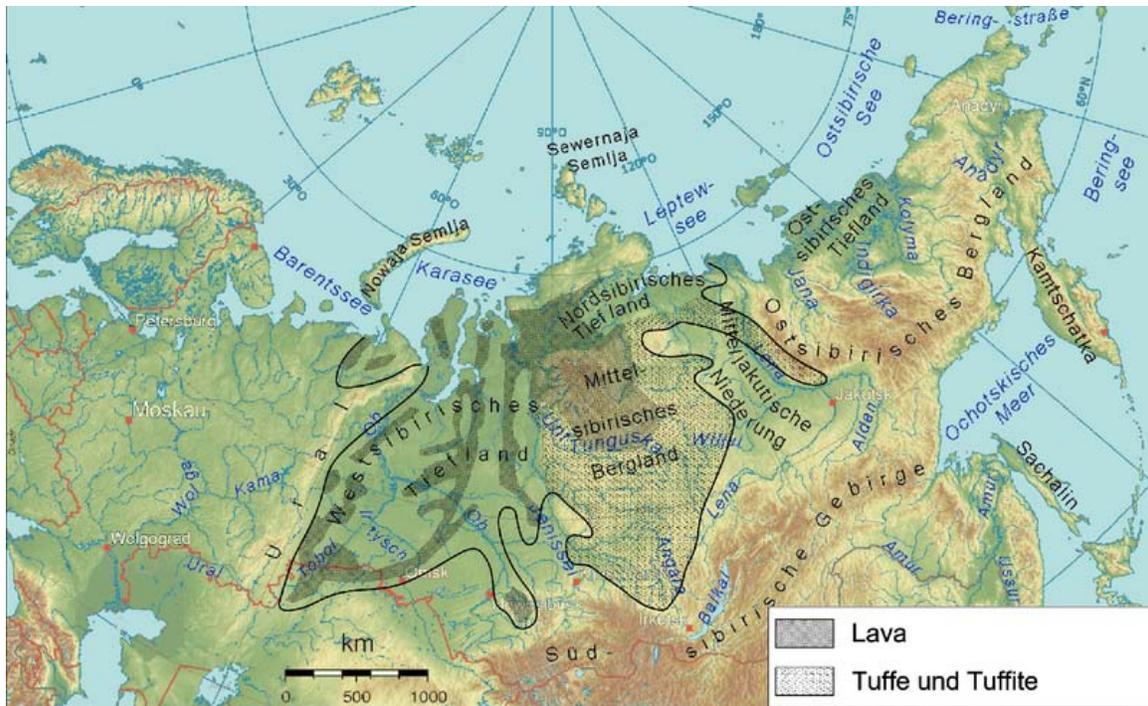


Effusive eruption of lava from Krafla, Iceland

Effusive eruptions

Effusive eruptions involve a relatively gentle, steady outpouring of lava rather than large explosions. They can continue for years or decades, producing extensive fluid mafic lava flows. For example, Kīlauea on Hawai‘i has continued erupting from 1983 to the present, producing 2.7 km^3 (1 cu mi) of lava covering more than 100 km^2 (40 sq mi). The largest effusive eruption in history occurred in Iceland during the 1783–1784 eruption of Laki, which produced about 15 km^3 (4 cu mi) of lava and killed one fifth of Iceland's population. The ensuing disruptions to the climate may also have killed millions elsewhere.

Eruption	Age (Ma)	Location	Volume (km³)	Notes
Mahabaleshwar–Rajahmundry Traps (Upper)	64.8	Deccan traps, India	9,300	
Wapshilla Ridge flows	~15.5	Columbia River Basalt Group, United States	5,000–10,000	Member comprises 8–10 flows with a total volume of ~50,000 km ³
McCoy Canyon flow	15.6	Columbia River Basalt Group, United States	4,300	
Umtanum flows	~15.6	Columbia River Basalt Group, United States	2,750	Two flows with a total volume of 5,500 km ³
Sand Hollow flow	15.3	Columbia River Basalt Group, United States	2,660	
Pruitt Draw flow	16.5	Columbia River Basalt Group, United States	2,350	
Museum flow	15.6	Columbia River Basalt Group, United States	2,350	
Moonaree Dacite	1591	Gawler Range Volcanics, Australia	2,050	One of the oldest large eruptions preserved
Rosalia flow	14.5	Columbia River Basalt Group, United States	1,900	
Joseph Creek flow	16.5	Columbia River Basalt Group, United States	1,850	
Ginkgo Basalt	15.3	Columbia River Basalt Group, United States	1,600	
California Creek—Airway Heights flow	15.6	Columbia River Basalt Group, United States	1,500	
Stember Creek flow	15.6	Columbia River Basalt Group, United States	1,200	



Extent of the Siberian Traps large igneous province (map in German)

Large igneous provinces

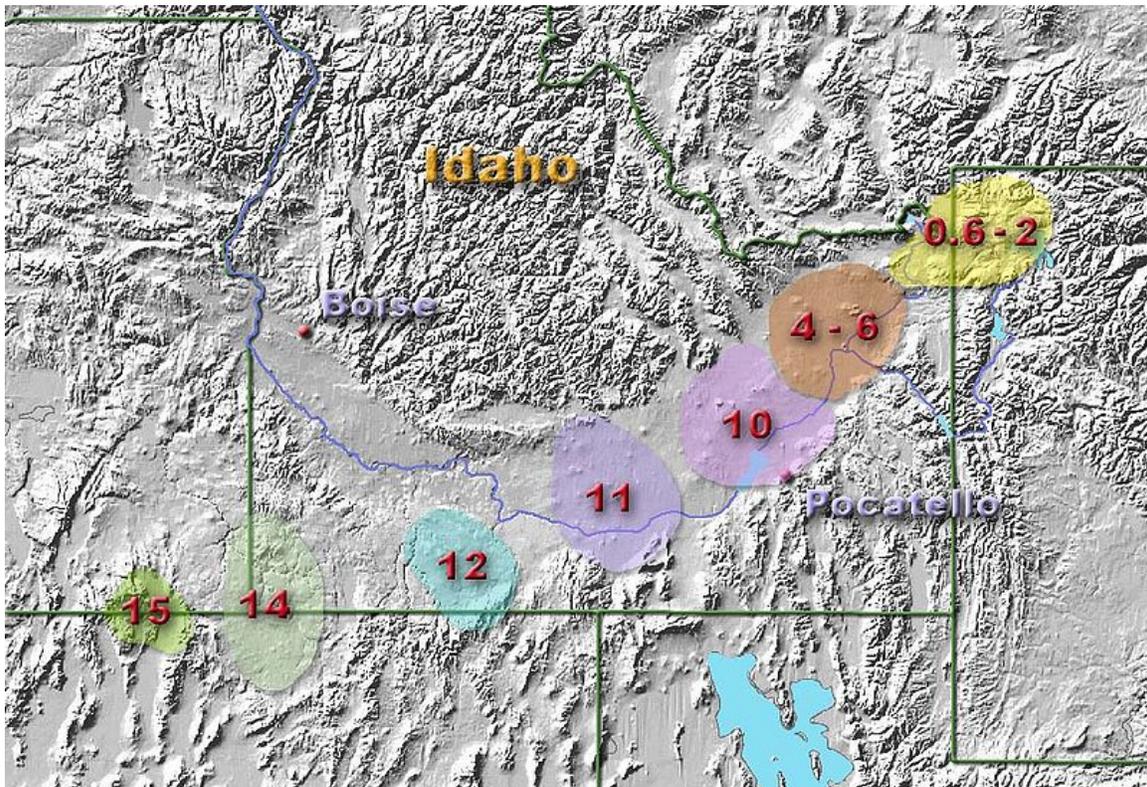
Highly active periods of volcanism in what are called large igneous provinces have produced huge oceanic plateaus and flood basalts in the past. These can comprise hundreds of large eruptions, producing millions of cubic kilometers of lava in total. No large flood basalt type eruptions have occurred in human history, the most recent having occurred over 10 million years ago. They are often associated with breakup of supercontinents such as Pangea in the geologic record, and may have contributed to a number of mass extinctions. Most large igneous provinces have either not been studied thoroughly enough to establish the size of their component eruptions, or are not preserved well enough to make this possible. Many of the eruptions listed above thus come from just two large igneous provinces: the Paraná and Etendeka traps and the Columbia River Basalt Group. The latter is the most recent large igneous province, and also one of the smallest. A list of large igneous provinces follows to provide some indication of how many large eruptions may be missing from the lists given here.

Igneous province	Age (Ma)	Location	Volume (millions of km³)	Notes
Ontong Java–Manihiki–Hikurangi Plateau	121	Southwest Pacific Ocean	59–77	Largest igneous body on Earth, later split into three widely separated oceanic plateaus, with a fourth component perhaps now accreted onto South America. Possibly linked to the Louisville hotspot. Linked to the Kerguelen hotspot. Volume includes Broken Ridge and the Southern and Central Kerguelen Plateau (produced 120–95 Ma), but not the Northern Kerguelen Plateau (produced after 40 Ma).
Kerguelen Plateau–Broken Ridge	112	South Indian Ocean, Kerguelen Islands	17	
North Atlantic Igneous Province	55.5	North Atlantic Ocean	6.6	Linked to the Iceland hotspot.
Mid-Tertiary ignimbrite flare-up	32.5	Southwest United States: mainly in Colorado, Nevada, Utah, and New Mexico	5.5	Mostly andesite to rhyolite explosive (.5 km ³) to effusive (5 km ³) eruptions, 25–40 Ma. Includes many volcanic centers, including the San Juan volcanic field.
Caribbean large igneous province	88	Caribbean-Colombian oceanic plateau	4	Linked to the Galápagos hotspot.
Siberian Traps	249.4	Siberia, Russia	1–4	Possibly the largest outpouring of lava on land ever recorded, thought to have caused Permian-Triassic extinction, largest mass extinction event ever.
Karoo-Ferrar	183	Southern Africa, Antarctica	2.5	Formed as Gondwana broke up
Paraná and Etendeka traps	133	Brazil/Angola and Namibia	2.3	Linked to the Tristan hotspot
Central Atlantic	200	Laurasia continents	2	Formed as Pangea broke up

Magmatic Province

Deccan Traps	65.5	Deccan Plateau, India	1.5	May have helped kill the dinosaurs.
Emeishan Traps	256.5	Southwestern China	1	Along with Siberian Traps, may have contributed to the Permian–Triassic extinction event.
Coppermine River Group	1267	Mackenzie Large Igneous Province/Canadian Shield	0.65	Consists of at least 150 individual flows.
Afro-Arabian flood volcanism	28.5	Ethiopia/Yemen/Afar, Arabian-Nubian Shield	0.35	Associated with silicic, explosive tuffs
Columbia River Basalt Group	16	Pacific Northwest, United States	0.18	Well exposed by Missoula Floods in the Channeled Scablands.

Known super eruptions



Location of Yellowstone Hotspot in Millions of Years Ago

Estimates of the volume of ejected material are given in parentheses.

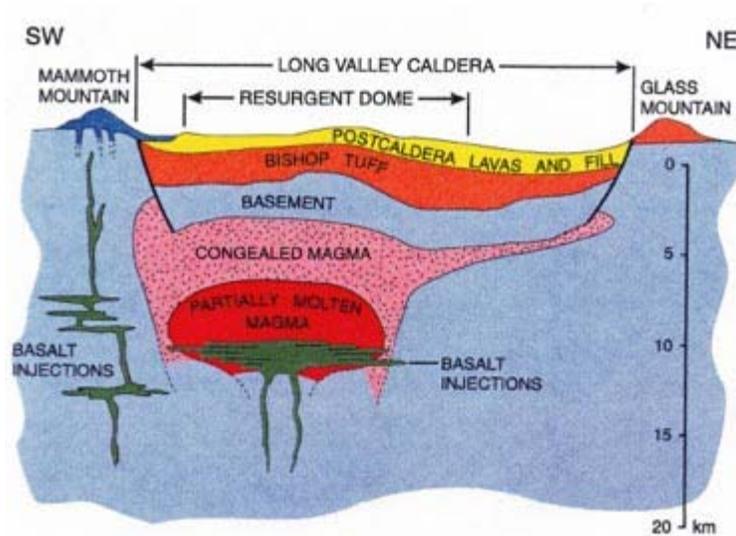
VEI 8

VEI 8 eruptions have happened in the following locations.

- Lake Taupo, Taupo Volcanic Zone, North Island, New Zealand—Oruanui eruption ~26,500 years ago (~1,170 km³)
- Lake Toba, Sumatra, Indonesia—~74,000 years ago (~2,800 km³)
- Whakamaru, Taupo Volcanic Zone, North Island, New Zealand—Whakamaru Ignimbrite/Mount Curl Tephra ~254,000 years ago (1,200-2,000 km³)
- Yellowstone Caldera, Lava Creek Tuff, Wyoming, United States, Yellowstone hotspot—640,000 years ago (1,000 km³)
- Island Park Caldera, Huckleberry Ridge Tuff, Idaho/Wyoming, United States, Yellowstone hotspot—2.1 million years ago (2,500 km³)
- Cerro Galan, Catamarca Province, Argentina—2.5 million years ago (1,050 km³)
- Atana Ignimbrite, Pacana Caldera, northern Chile—4 million years ago (2,500 km³)
- Heise volcanic field, Kilgore Tuff, Idaho, United States, Yellowstone hotspot—4.5 million years ago (1,800 km³).
- Heise volcanic field, Blacktail Tuff, Idaho, United States, Yellowstone hotspot—6.6 million years ago (1,500 km³).
- La Garita Caldera, Colorado, United States—Source of the enormous eruption of the Fish Canyon Tuff ~27.8 million years ago (~5,000 km³)

The Lake Toba eruption plunged the Earth into a volcanic winter, eradicating an estimated 60% of the human population (although humans managed to survive, even in the vicinity of the volcano). However the coincidental agreement in above sources about percentage value of extinction is contrary to differing estimates of human population size at that time.

VEI 7



Cross-section through Long Valley Caldera

VEI-7 volcanic events, less colossal but still supermassive, have occurred in the geological past. The only ones in historic times are Tambora, in 1815, Lake Taupo (Hatepe), around 180 CE, and possibly Baekdu Mountain, 969 CE (± 20 years).

- Tambora, Sumbawa Island, West Nusa Tenggara, Indonesia—1815 (160 km^3), the following year 1816 became known as the "Year Without a Summer"
- Baekdu Mountain, China/North Korea—969 CE ($96 \pm 19 \text{ km}^3$)
- Lake Taupo, Taupo Volcanic Zone, North Island, New Zealand—Hatepe eruption ~181 CE (120 km^3)
- Kikai Caldera, Ryukyu Islands, Japan—~6,300 years ago (~4,300 BCE) (150 km^3)
- Macauley Island, Kermadec Islands, New Zealand—~6,300 years ago (~4,300 BCE) (100 km^3)
- Aira Caldera, Kyūshū, Japan—~22,000 years ago (~ 110 km^3)
- Rotoiti Ignimbrite, Taupo Volcanic Zone, North Island, New Zealand—~50,000 years ago (~ 240 km^3)
- Campi Flegrei, Naples, Italy— $39,280 \pm 110$ years ago (500 km^3)
- Aso, Kyūshū, Japan—four large explosive eruptions between 300,000 to 80,000 years ago (last one $>600 \text{ km}^3$)
- Reporoa Caldera, Taupo Volcanic Zone, North Island, New Zealand—230,000 years ago (~ 100 km^3)* I. A. Nairn; C. P. Wood and R. A. Bailey (December 1994). "The Reporoa Caldera, Taupo Volcanic Zone: source of the Kaingaroa Ignimbrites". *Bulletin of Volcanology* **56** (6): 529–537. doi:10.1007/BF00302833. Retrieved 2010-09-16.
- Mamaku Ignimbrite, Rotorua Caldera, Taupo Volcanic Zone, North Island, New Zealand—240,000 years ago ($>280 \text{ km}^3$)

- Matahina Ignimbrite, Haroharo Caldera, Taupo Volcanic Zone, North Island, New Zealand—280,000 years ago (~120 km³)
- Long Valley Caldera, Bishop Tuff, California, United States—~760,000 years ago (600 km³)
- Valles Caldera, New Mexico, United States—~1.15 million years ago (~600 km³)
- Mangakino, Taupo Volcanic Zone, North Island, New Zealand—three eruptions from 0.97 to 1.23 million years ago (each > 300 km³)
- Henry's Fork Caldera, Mesa Falls Tuff, Idaho, United States, Yellowstone hotspot—1.3 million years ago (280 km³)
- Pastos Grandes Ignimbrite, Pastos Grandes Caldera, 2.9 million years ago (>820 km³)
- Heise volcanic field, Walcott Tuff, Idaho, United States, Yellowstone hotspot—6.4 million years ago (750 km³).
- Bruneau-Jarbidge, Idaho, United States, Yellowstone hotspot—~10–12 million years ago (>250 km³) (responsible for the Ashfall Fossil Beds ~1,600 km to the east)
- Bennett Lake Volcanic Complex, British Columbia/Yukon, Canada—~50 million years ago (850 km³)