5 Climate Changes of the Past

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Earth's climate has changed tremendously over its 4.6-billion-year history!

The planet has slowly evolved from an uninhabitable ocean of magma to a radiation blasted ocean to a ball of ice and then settled into a long maturity over the past few hundred million years. Life has evolved along with the planet and in fact has played many key roles in shaping climate as well as being shaped by climate.

In addition to long-term changes there are swings back and forth from very hot to very cold conditions and the occasional extreme disruptions that seem to reset almost everything. It's a remarkably dynamic and fascinating story, and it has profound implications for what we can expect of modern climate change in the coming decades and centuries.

5.1 Billions of Years: Maturation of the Planet

5.1.1 Origin and Composition of the Earth

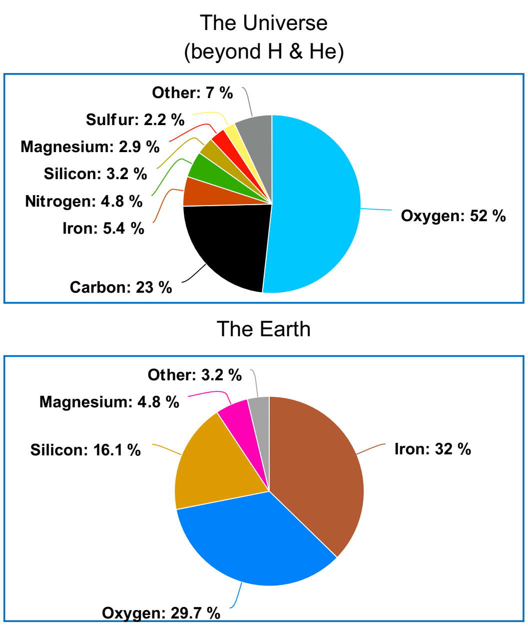


Figure 5-1: Abundance of chemical elements in the universe (top) and the Earth (bottom). The lightest two elements (hydrogen and helium) comprise more than 99% of ordinary matter, but the next most abundant stuff is very familiar to us on Earth

The solar system was formed by gravitational collapse from a huge cloud of interstellar dust and gas about 4.567 billion years ago. The cloud of gas and dust from which the solar system formed swirled and fell in on itself under its own weight. The center of this collapsing blob (the "solar nebula") was so dense and heavy that hydrogen gas was crushed out of existence at its core, igniting thermonuclear fusion in the Sun that powers all stars.

The material composition of the Sun and everything that orbits the Sun is pretty much identical to the stuff that's strewn along the disk of our Milky Way Galaxy – the processed remains of previous generations of stars that formed and died before our Sun was formed.

Most of the cosmos (and therefore the solar system) is hydrogen and helium, but the next most abundant elements are quite familiar to us: oxygen, carbon, iron, nitrogen, and silicon (Fig 5-1). The outer part of the solar nebula, far from the nuclear fire, was cold enough for the lighter elements to condense and freeze as ice made of water (H_2O), carbon dioxide (CO_2), methane (CH_4), and ammonia (NH_3). Closer to the central flame, the inner planets were broiled dry so are mostly made from solid oxides (minerals) of metals such as silicon and iron.

Many millions of years later the inner solar system was bombarded by huge collisions as Jupiter migrated into its current orbit. One of the biggest of these collisions almost destroyed the

Earth 4.5 billion years ago and formed the Moon from debris ejected in the resulting explosion. The incredible violence of these events probably melted our entire planet. In the resulting swirling ocean of molten rock, heavy metals like iron and nickel sank to form Earth's core, leaving a mantle of oxidized iron, magnesium, silicon, and other rock-forming elements on the outside.

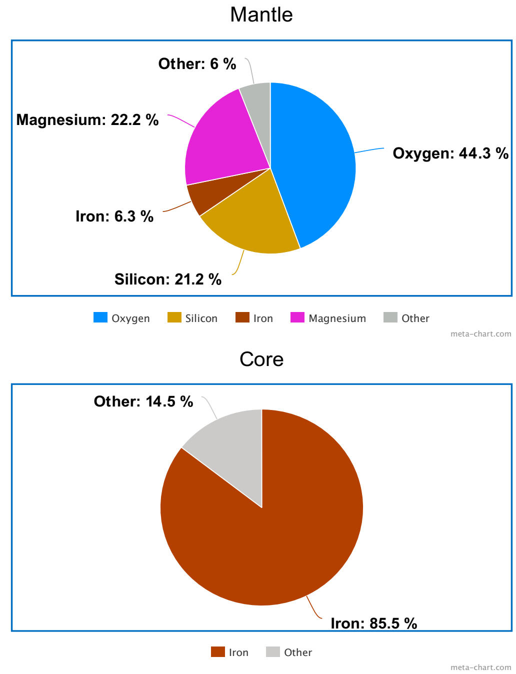


Figure 5-2: Composition of the Earth's mantle (top) and core (bottom)

Volatile elements like hydrogen, carbon, and nitrogen were probably delivered from the outer solar system by colossal collisions during the heavy bombardment period. As the magma ocean froze into rock, these volatile elements floated on top to form an atmosphere of superheated steam that later condensed to form an ocean of liquid water.

The early Sun was much less bright and hot than today, providing around 30% less heat energy to the Earth than it does for today's climate system. If the Sun were to lose 30% of it's brightness now, our planet would freeze solid. Luckily, early Earth's Greenhouse Effect was far more powerful than it is now, so our planet continued to develop as the Sun slowly brightened over billions of years.

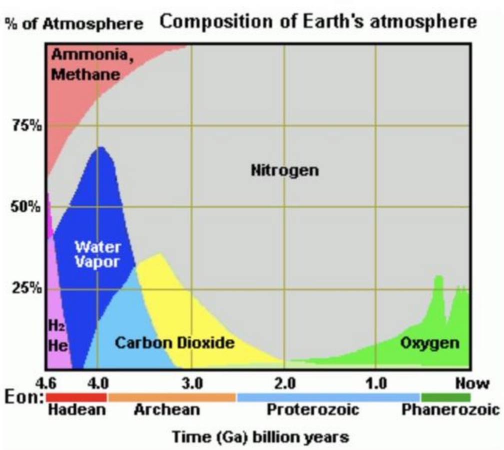


Figure 5-3: Proportional composition of the atmosphere over geologic time. Wikimedia Commons

The atmosphere at that time (around 4.2 billion years ago) was probably very hot and dense, made largely of carbon dioxide (CO_2) and H_2O vapor with a lot of methane (CH_4) and ammonia (NH_3). Without any free oxygen in the air, reduced compounds like CH4 were chemically stable and provided a very strong absorption of outgoing longwave radiation (OLR).

Another very important aspect of the anoxic early atmosphere was that there was no ozone layer, because ozone (O3) is made from oxygen (O2). Deadly solar ultraviolet (UV) radiation blasted Earth's surface and kept it sterile even of the primitive microbes that could only grow where they were protected by seawater.

5.1.2 Life Transformed the Earth and Climate

The oldest evidence of life on Earth is debated but indicates that life got started between 4 billion and 3.7 billion years ago, probably associated with volcanic vents on the sea floor. By 3.5 billion years ago single-celled microbes began using solar energy to store chemical energy in sugars that they manufactured from CO_2 and H_2O through the process of ***photosynthesis***.

Free oxygen (O_2) is released as a byproduct of photosynthesis. Free o2 is extremely reactive and its buildup as a dissolved component in the oceans completely transformed the chemistry of seawater. Over time the chemically reduced compounds in the oceans were consumed or precipitated out as sedimentary rocks.

By about 2 billion years ago there was so much dissolved oxygen in the oceans that it began to diffuse into the overlying atmosphere. As the air became oxidized, reduced compounds like CH_4 and NH_3 were consumed, dramatically weakening the Greenhouse Effect. As strong absorbers were "burned off" by oxidation, Earth's OLR increased, and surface temperature dropped sharply. Polar ice caps formed and spread toward the tropics. Eventually nearly the entire surface was covered in ice and snow! This climate catastrophe is known as ***"Snowball Earth."***

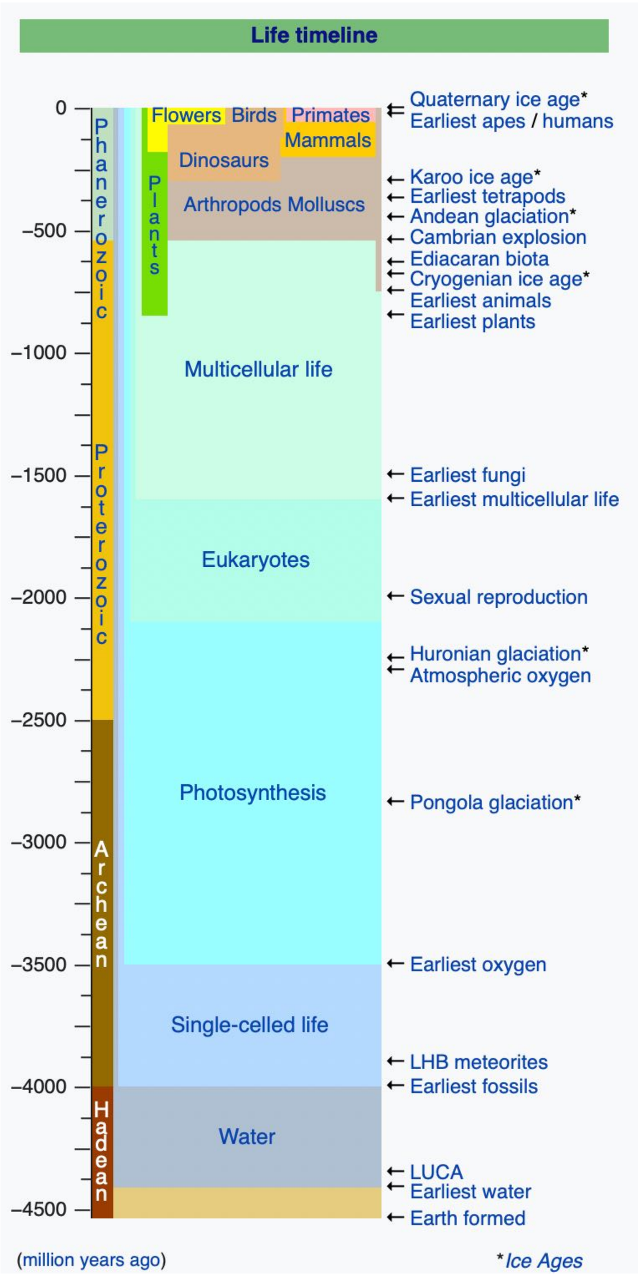


Figure 5-4: Timeline of Earth and Life. Wikimedia commons

During Snowball Earth episodes, microbial life continued its slow evolution in the oceans. The global hydrologic cycle slowed to a crawl with evaporation from the frozen ocean surface blocked by ice. With rain and snowfall effectively stopped, and so did most erosion and chemical weathering of rock. Volcanic degassing continued to pour CO_2 into the air but there was nothing to consume it. Over millions of frozen years, CO_2 built up until the Greenhouse Effect eventually became strong enough to melt the ice. Snowball Earth episodes happened at least three times over the period from about 2 billion until 0.7 billion years ago as the climate system swung wildly around following the Great Oxidation Event brought about by the rise of photosynthesis.

During this period, life evolved very slowly. For billions of years, the only living things on Earth were fairly simple single-celled microbes. Partial melting of rock produced gray granite that accumulated into blocks of higher terrain, eventually forming continents. The accumulation of free O_2 in the air allowed the UV-protective ozone layer to form, greatly improving surface conditions.

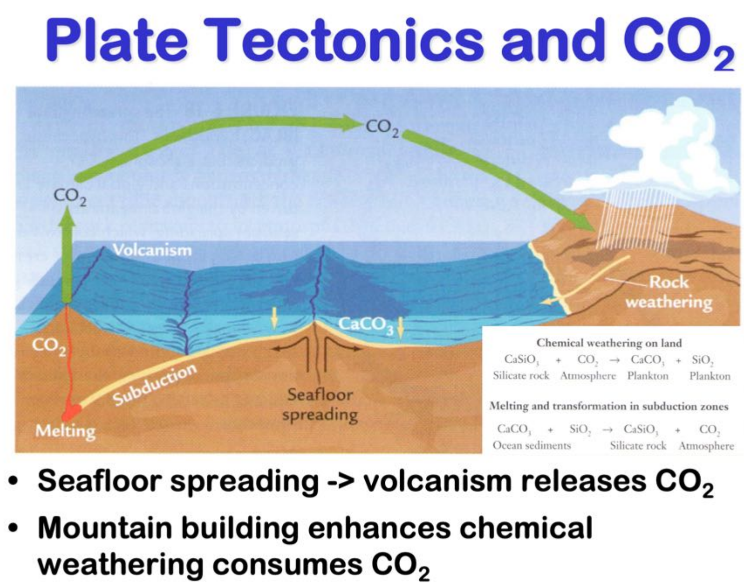
Finally, about 700 million years ago climate stabilized and multicellular life exploded into a diverse biosphere for reasons that nobody really understands.

5.2 Millions of Years: A Geologic CO_2 Thermostat

Beginning about 540 million years ago, large complex plants and animals left abundant skeletal remains as fossils in sedimentary rock. This fossil record allows much more detailed reconstruction of climate and evolution over the past half-billion years (10% of Earth's history) than the previous eons (90% of Earth's history).

Despite the ancient shocks of Snowball Earth, our current climate is among the coldest our planet has ever been. Earth has only rarely sported polar ice caps and has nearly always been much warmer than today. Continental drift has repeatedly reorganized the shape and size of the ocean basins, transforming the way currents pump heat form the tropics to the poles and the partition of heat between air and deep water.

By far most of Earth's climate change over the past 500 million years has been driven by changes in the strength of the Greenhouse Effect. These changes are driven by very slow buildups and drawdowns of CO_2 over tens of millions of years as a result of tiny imbalances between volcanic degassing and chemical weathering that consumes CO_2 to form limestone (calcium carbonate, $CaCO_3$) in the oceans.



5.2.1 Geologic Carbon Cycling

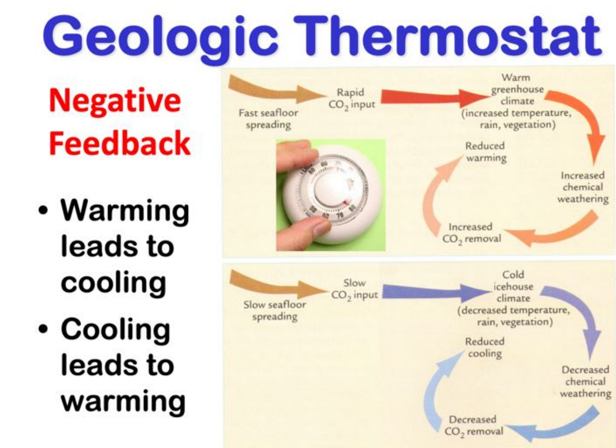
Earth's crust is divided into a few dozen brittle "plates" that move around over many millions of years driven by slow convection in the hot underlying mantle. Where ocean plates diverge (pull apart), molten magma rises from below to build new crust and volcanic vents release CO_2 into the oceans and atmosphere.

Conversely where continental plates converge (collide), mountain ranges rise slowly into the sky. Steep mountains with exposed rock and lots of rain and snow erode and break up into boulders and cobbles and pebbles and sand. Fragmented rock exposes unstable minerals to chemical breakdown by carbonic acid (CO_2 dissolved in rainwater), consuming atmospheric CO_2 and running down streams and rivers into the sea. Marine plants and animals use these dissolved minerals to make shells and skeletons that are deposited on the ocean floor as limestone (CaCO3).

Where ocean plates converge, CaCO3 in sediments is caried down in subduction zones to be remelted by geothermal heat at great depth. This is the source of CO_2 in volcanic gases that is returned to the atmosphere at seafloor spreading zones and other volcanoes.

5.2.2. Negative CO_2 Feedback

Over tens of millions of years, the rate of CO_2 production by volcanic emissions is nearly matched with the rate of CO_2 consumption by chemical weathering on land. But through the vagaries of plate tectonics, volcanic degassing or weathering can sometimes get a little ahead and the geologic carbon cycle gets slightly out of balance. In that case CO_2 slowly rises or falls for long periods.



As CO_2 builds up due to a slight excess of volcanism over weathering, the increased Greenhouse Effect causes Earth to retain outgoing longwave radiation and surface temperature rises. As we saw in Module 4, positive climate forcing is amplified by increased water vapor, reduced albedo, and changes in clouds leading to hothouse climates that may persist for as much as 100 million years. The hydrologic cycle speeds up and global precipitation increases. Snow and glacial ice build up on mountain ranges. The rate of erosion and chemical weathering increases, and CO_2 is drawn down by the increased formation of CaCO3 in ocean sediments. Eventually CO_2 is drawn down far enough to cool global climate back off.

Conversely, a slowdown of volcanism or an increase in erosion and weathering can allow CO_2 to fall. Cooling is enhanced by reduced water vapor, increased albedo, and changes in clouds. This results in an "icehouse climate" that may persist for many millions of years and be punctuated by dozens of shorter Ice Ages. Land climates dry out, erosion and weathering slow, and the rate of CaCO3 deposition in the deep ocean is decreased. Eventually the CO_2 from volcanism builds back up to the point that the icehouse period is over.

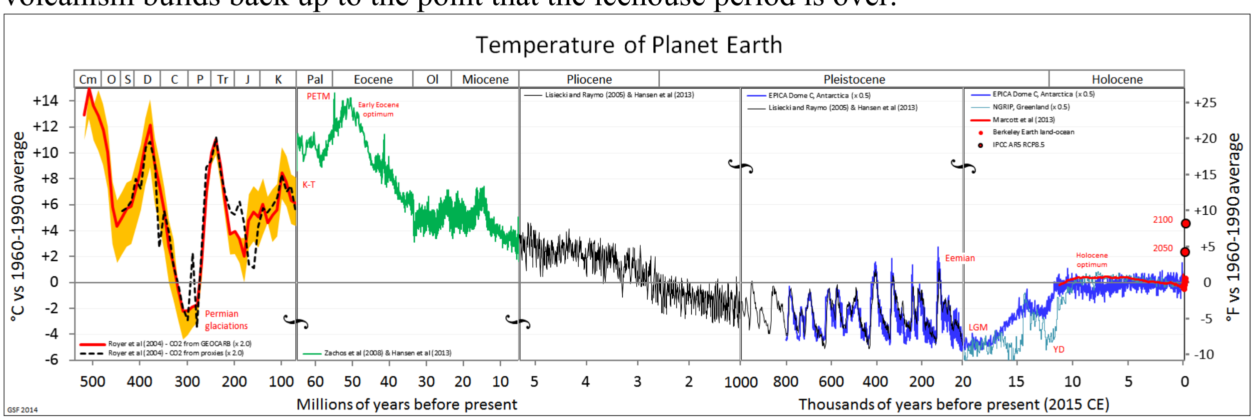


Figure 5-5: Half a billion years of climate change. Note the four breaks in scale on the time axis! Enormous swings in climate over hundreds of millions of years were followed by slow steady cooling over the past 50 million years and then the oscillations of ice ages and warmer interglacial periods over the past couple of million years. Wikimedia Commons; CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1240577

Over hundreds of millions of years Earth's climate has experienced enormous fluctuations (Fig 5-5). The negative feedback provided by the geologic carbon cycle has also stabilized climate within this broad range, allowing life to evolve incredible diversity.

5.2.3 Climate Catastrophes and Mass Extinctions

Over the Phanerozoic (visible fossils) era, most climate changes have been gradual enough for evolution to allow life to adapt. But several times in the past half-billion years there have been much faster changes which happened too quickly for life to adapt and led to tremendous loss of biodiversity. These events are called "***mass extinctions***."

Two mass extinction events were so severe that they essentially reset biological evolution. These ended the Paleozoic ("early life") and Mesozoic ("middle life") Eras. The end of the Paleozoic 252 million years ago is also known as the "Great Dying" and wiped out about 80% of all species. Recovery from this catastrophe took many millions of years and led to the age of dinosaurs. The end of the Mesozoic 66 million years ago also killed off about ¾ of all species, ending the reign of dinosaurs and leading to the emergence of mammals as a dominant class of animal.

The ***Great Dying 252 million years*** ago was apparently caused by a catastrophic increase in atmospheric CO_2 and temperature associated with a gigantic outpouring of molten rock through carbon-rich sediments in what is now Siberia. Toxic gases and rainfall and rapid warming on land killed so much vegetation that rivers carried floods of dead material into the oceans for millennia. The oceans were acidified by dissolved CO_2 and rotting organic matter so that marine life depending on CaCO3 were wiped out, leading to complete collapse of ocean food webs. Conditions were so dire that it took 10 to 25 million years for evolution to restart the development of biodiversity in the early Mesozoic.

For the next 185 million years dinosaurs came to dominate life on Earth. They diversified to fill many ecological niches both on land and in the oceans. But their reign was abruptly ended by the ***impact of a comet or asteroid 66 million years ago*** near what is now the Yucatan Peninsula of Mexico. The impactor is estimated to have been 10 km in diameter traveling at around 25 km per second and caused an almost inconceivable explosion and worldwide shockwave. The shock wave incinerated an enormous region, destructive debris and tsunami waves swept across thousands of km. The entire world was plunged into darkness and freezing temperatures as sunlight was blocked by dust and smoke, destroying food webs. Recovery was much faster than the extended catastrophe of the Great Dying, with mammals flourishing to become dominant over a few million years at the beginning of the Cenozoic ("modern life") Era.

5.2.4 Slow Decline of CO_2 and Cooling through the Cenozoic

Since the day the dinosaurs died, the main event in Earth's climate has been a slow, steady, and substantial cooling from hothouse to icehouse that began about 50 million years ago. As in previous long-term cooling episodes the decline is due to drawdown of CO_2 by a slight excess of chemical weathering over the rate of emission by volcanic outgassing. There are at least three significant geologic processes that have contributed to this remarkable change:

1) continent-continent collision of India with Asia that began about 50 million years ago, raising the Himalaya, Tibetan Plateau, and other high terrain on the “roof of the world” across central Asia which led to massive amounts of erosion and weathering;
2) movement of Antarctica into the polar position which allows it to accumulate deep permanent continental ice that increases planetary albedo; and
3) the opening of the Drake Passage and Southern Ocean providing a land-free corridor spanning all longitudes between 55 and 70 south latitudes with the resulting Circumpolar Current isolating the deep south from warm tropical waters.

Atmospheric CO_2 has dropped by about a factor of four during the past 50 million years, with global temperatures falling perhaps more than 15 Celsius on average over that time (Fig 5-5). Continents dried out as global temperatures cooled, and enormous grasslands evolved to cover huge areas grazed by herds of mammals for the first time. Continental ice sheets began growing in Antarctica 34 million years ago for the first time since the late Paleozoic 300 million years ago.

Ice sheets began to appear over huge areas of the northern continents much more recently and the ice-albedo feedback accelerated the descent into a deep icehouse climate just in the most recent 2 million years.

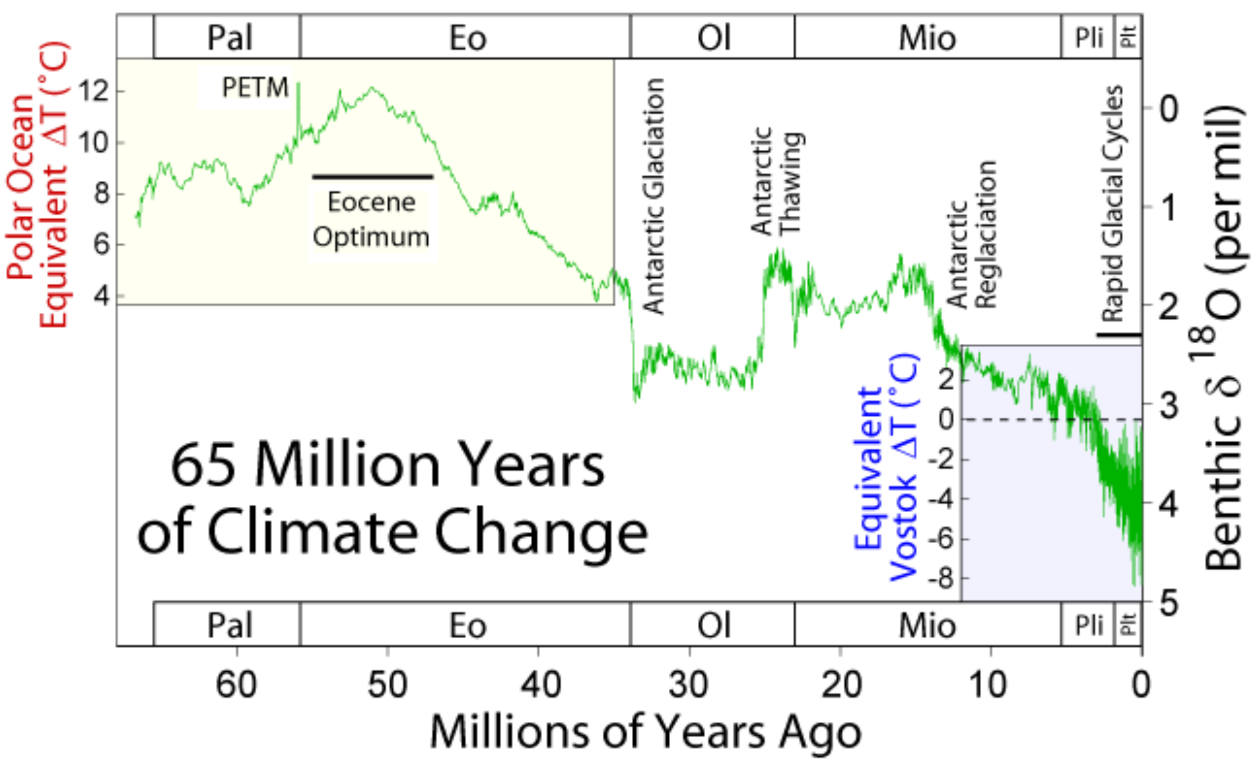


Figure 5-6: Slow but profound cooling during Earth's Cenozoic (new life) Era. Wikimedia Commons

5.3 Thousands of Years: Ice Age Cycles and Earth's Orbit

Over just the past two million years or so, ***Earth's climate has oscillated wildly*** between ***extremely cold Ice Age conditions*** in which huge regions were covered with land and sea ice and ***warmer interglacial periods*** in between in which ice recedes back toward the poles. These quasi-periodic Ice Age cycles have come and gone approximately every 100,000 years so around 20 times since they started. This period has also coincided with human evolution from the emergence of Homo erectus and the first use of fire about 1.9 million years ago.

Please keep two things in mind about Ice Age climate cycles:

1) ***They're huge!*** Climate changes so much on a 100,000 year cycle that the coastlines of the world and the map of vegetation are completely redrawn as vast amounts of water move from oceans to land ice sheets and back again.
2) ***They're new!*** Although Earth has experienced well over a dozen of these episodes since the discovery of fire, there were no such episodes for hundreds of millions of years before. We must look back well before the earliest dinosaurs to find the previous series of periodic Ice Age cycles.

Before we look at the mechanisms responsible for Earth's spectacular Ice Age cycles, let's think for a bit about the nature of glaciers and the way they inform our understanding of Ice Ages.

5.3.1 Thinking about Glaciers

Glaciers are big chunks of ice that move under the influence of gravity. They are most familiar to us in high mountains where more snow accumulates in winter than can melt in summer. Old snow gets deeper and deeper at the top of a glacier and its weight packs the snow into solid ice that starts to slide down the mountain. If enough snow accumulates at the top of a glacier, ***solid ice can flow like toothpaste*** down well below the ***"snowline" which marks the elevation beyond winter snowfall exceeds summer melting***. Above the snowline, ice accumulates and flows downhill. Below the snowline, ice arrives by flowing from above and melts to form streams and rivers.

The bottom (***"terminus"***) of the glacier is the point at which the rate of melting exceeds the rate of downhill flow. As glaciers flow downhill, they pluck up some of the underlying rock which freezes into and is carried along with the ice as if by a conveyor belt. At the terminus broken and ground-up pieces of rock fall out of the melting ice to be deposited in a pile of boulders, sand, and gravel called a ***"terminal moraine."***

All this has been known to people living in high mountain valleys around the world for thousands of years. Villages in the Alps, Andes, and Central Asia have historically developed below glaciers, benefiting from reliable summer meltwater that feeds crops, pastures, and livestock. Local people learned the ins and outs of glacial landforms and by the mid-19th Century scientists recognized that these landforms were found all over Europe.

Eventually it dawned on people that there had previously been an “Age of Ice” that left characteristic piles of sand and gravel all over the northern world. By the beginning of the 20th Century these deposits had been mapped and it was clear that gigantic glaciers in the form of continental ice sheets had covered huge expanses of North America, Europe and Asia and that mountain glaciers in the southern hemisphere had also greatly expanded during past Ice Ages.

Modern Mountain Glaciers

Below are some photographs I took on a family vacation to Chamonix in the French Alps in 2006. Chamonix is about 2000 feet (600 m) above sea level but sits at the base of Mont Blanc, the highest mountain in western Europe at over 15000 feet (5000 m). The top of Mont Blanc is well above the snowline, and deeply buried in solid glacial ice. Ice pours off the massif and drips slowly down into valleys that are carved by the flowing ice itself. One of the most prominent of these gigantic mountain glaciers is the Bossons Glacier which hangs over the valley. Its terminus has retreated thousands of feet up the mountain due to a warming climate since travel writers visited it more than 240 years ago.

Figure 5-7: Mont Blanc (15,777 feet) towers above Chamonix in the French Alps. Our hotel L'Aiguille du Midi is named for a spectacular pillar of rock at 12,000 feet elevation on Mont Blanc, a popular tourist destination because it is easily reached by an incredible cable car which rises more than 10,000 feet in under 10 minutes.

Figure 5-8: Bossons Glacier hanging from Mont Blanc. In the 17th Century, the terminus of Bossons reached right down into the village of Chamonix itself. Note the heavy crevassing of the ice as it flows slowly down the irregular mountainside.

Figure 5-9: Looking down Bossons Glacier from L'Aiguille du Midi ("the needle of noon") at the top of the cable car. The village of Chamonix is visible in the valley more than 10,000 feet below. Both crevasses and the retreat of the glacier from its lower reaches are obvious in the photo.

Figure 5-10: The summit of Mont Blanc from L'Aiguille du Midi. Note the incredibly thick masses of glacial ice and also the tiny trails left by alpinists!

Not Quite a Glacier

Below are some photographs I took at a mountain cabin in the Snowy Range of southern Wyoming about 100 miles northwest of the CSU campus. The cabin is 10,500 feet (3200 meters) above sea level and receives about a meter of precipitation per year, the vast majority as snow. Snow begins to accumulate each October and the snowpack typically increases in water content until May. In heavy snow years the cabin is buried to the roofline when we first reach it at the end of May.

Very long warm days at summer solstice melt eight months' worth of accumulated snow in a matter of weeks, but we often still have big snowdrifts in the meadows in late July. There's typically just a few dry weeks between the melting of the last of the previous winter's snow and the beginning of the next year's snow accumulation in October.

It's easy to imagine that if our mountain summers were just a few degrees cooler there might still be leftover piles of filthy late-summer ice when the snow starts piling up again in the fall. If that happened for a few hundred centuries, an ice sheet might easily grow again and flow down past Centennial toward Laramie. That's exactly what happened around 100,000 years ago and the terminal moraine can still be clearly seen along Wyoming Highway 130 where it crosses the Little Laramie River.

Figure 5-11: Very deep June snowpack at our mountain cabin

Figure 5-12: Stovepipes protrude from our neighbors' cabin through summer solstice snowpack

Figure 5-13: Sledding on snowdrifts in the cabin meadow in late July

Figure 5-14: Winter is Coming! September snows will either melt in a few days or become the base for a new winter's snowpack

The Ends of the Earth

At the other end of the spatial scale, there are ice sheets covering Antarctica and Greenland that are thousands of meters thick and cover an area larger than the United States. They have a lot in common with mountain glaciers: they form because more snow falls in summer than can melt in summer; they flow across the landscape due to gravity, deforming under the influence of their own weight; they carry enormous amounts of rock debris which they deposit in terminal moraines. But they are vast beyond our experience, comprising more than 95% of all the fresh water on Earth.

The Greenland Ice Sheet and the sea ice to its north is all that remains of the polar great ice cap that smothered the northern world until 100 centuries ago. It's nearly 10,000 feet thick at its center and stretches 1500 miles from the high Arctic to the middle of the North Atlantic Ocean. It covers more than 80% of Greenland, whose name reflects one of the most notorious real estate scams in history (sold to poor famers in Iceland). If and when the ice in Greenland melts, global average sea level will rise about 7 meters (23 feet).

The Antarctic Ice sheet is nearly ten times the size of Greenland. The ice is more than 3000 meters thick and covers 98% of the continent. It's much older than the Greenland Ice Sheet and contains enough water to raise global sea level by 60 meters (about 200 feet). Most of the ice sheet is very cold and can't melt anytime soon, but west of the Antarctic Mountains the base of the ice is far below sea level. That ice is quite vulnerable because rising oceans can float the glaciers, releasing them from friction at their bases. Much of the West Antarctic Ice Sheet is therefore in danger of melting due to modern global warming.

5.3.2 Reconstructing Ice Age Climate Change

Over the past century, people have learned a great deal about Ice Age climates by studying samples of mud from the bottom of the ocean and air from bubbles contained in ice retrieved from Greenland and Antarctica.

Continental ice sheets contain an incredible amount of water, all of which must be transferred from the oceans by precipitation to build the ice sheet as climate cools. Water (H_2O) contains two stable isotopes of oxygen: ^{16}O is more common with 8 protons and 8 neutrons whereas ^{18}O is heavier with 10 neutrons. When water evaporates form the oceans to build ice sheets the lighter ^{16}O is preferentially removed and the remaining oceans become measurably enriched in the heavier ^{18}O that's left behind. This isotopic enrichment of the ice-age oceans is recorded in microscopic fossils deposited in mud on the sea bottom.


Glomar Challenger

Beginning in the 1960s, deep sea drilling programs retrieved deep sea cores from all over the world and climate scientists began reconstructing changes in global ice volume from the isotopic composition of microfossils in those mud cores. They discovered that the total amount of ice in the world had grown and shrunk over and over for millions of years, beating with different frequencies or cycles of different periods. The dominant period for growth and shrinking of continental ice was found to be about 100,000 years over the past million years or so, but only about 40,000 years for a million years before that.


Mechanical drill head, showing cutting teeth

In the 1980s, scientists began drilling deep into the continental ice sheets themselves, bringing back cores of glacial ice thousands of meters long to study in laboratories back home. The ice itself records climate via the isotopes in the water itself, just as the oceanographers had found earlier. But even better, the ice contains bubbles of fossil air that became trapped among snowflakes many thousands of years ago. These bubbles can be analyzed with modern laboratory instruments, revealing slow cyclic changes in the composition of trace gases in the atmosphere over Ice Age and interglacial cycles.


Ice core sample taken from drill

Ice core gas analysis revealed immense shifts in the concentrations of greenhouse gases (CO_2, CH_4, and N_2O) leading to a much weaker Greenhouse Effect during ice ages and much stronger Greenhouse Effect during the warmer interglacial periods. This was completely unexpected and hard to explain! During cold Ice Ages atmospheric CO_2 drops to about 180 ppm (parts per million). This means that air bubbles in samples of Antarctic ice deposited during Ice Ages contain about 180 molecules of CO_2 for every 1 million molecules of air. By contrast, bubbles from ice deposited during warmer interglacials contain about 280 ppm (more than half again as much). Other greenhouse gases follow the same pattern. What can account for these huge shifts in the composition of the atmosphere?

A store of core samples

The solubility of CO_2 in seawater is quite sensitive to temperature, with cold water holding about twice as much CO_2 as warm water. This is precisely the same ("carbonation") chemistry that makes cold beer or soft drinks bubbly and causes them to go flat when left on the kitchen counter too long. Initially some scientists proposed that the huge swings in Ice Age CO_2 might have been a positive (amplifying) feedback in which cold glacial seas simply dissolved more CO_2 and then released it when they warmed up. But past sea-surface temperatures reconstructed from microfossils in ocean bottom mud show that this effect can account for no more than about 30% of the big Ice Age swings in CO_2.

It now appears that a combination of temperature-dependent CO_2 solubility, changes in ocean mixing, and massive fertilization of marine phytoplankton by windblown continental dust deposited during Ice Ages drives the big shifts in CO_2 associated with glacial climate cycles. Note that these mechanisms do NOT suppose that changes in CO_2 and other greenhouse gases actually CAUSE the timing of Ice Ages. Rather, the changes in ocean CO_2 amplify some existing climate forcing, making Ice Age climate swings stronger than they would otherwise be. This positive carbon cycle feedback reinforces the strong ice-albedo feedback in which colder

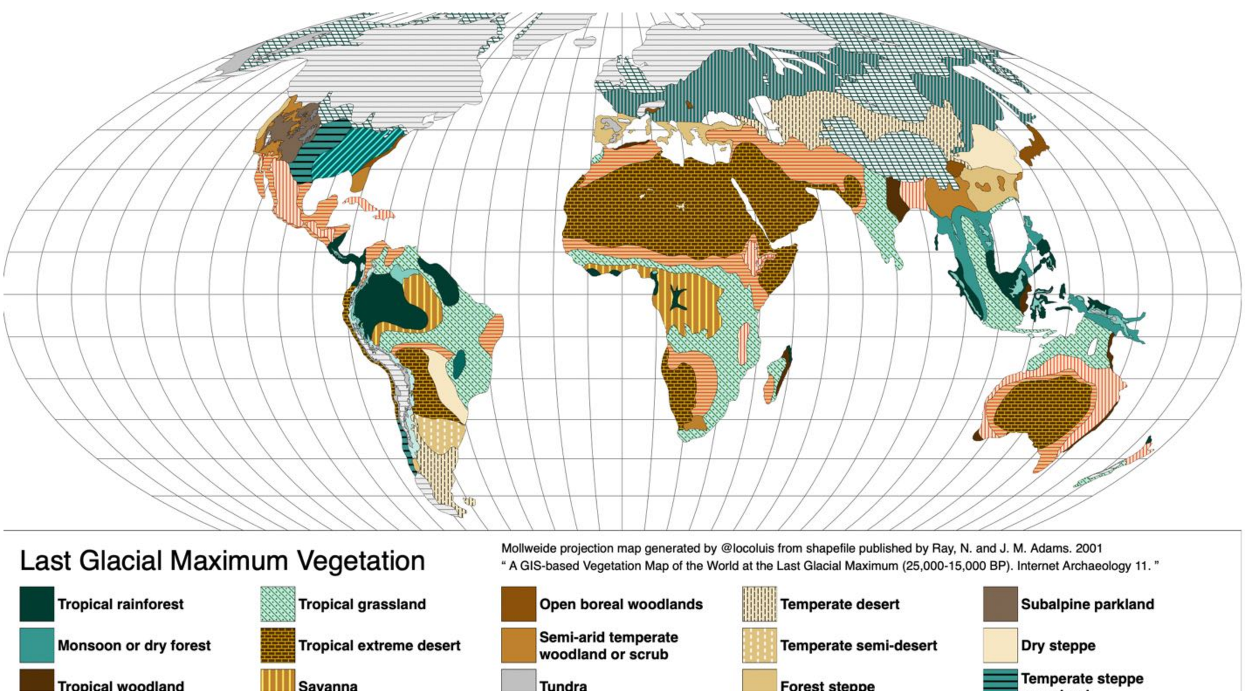


Figure 5-15: Map of coverage by ice sheets and vegetation at the Last Glacial maximum (18,000 years ago). Creative Commons license

climates are associated with higher planetary albedo which amplifies the cooling (and subsequent postglacial warming).

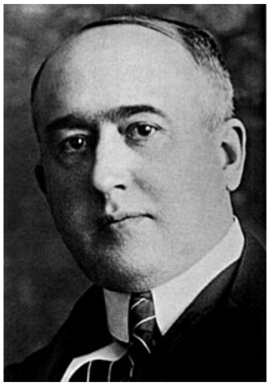
The most recent Ice Age reached its maximum intensity (coldest temperatures, maximum ice extent) about 18,000 years ago. Continental ice at that time reached well into what are now temperate latitudes. In North America, the Laurentide Ice Sheet was centered where Hudson Bay lies today and reached southward to carve the basins of the Great Lakes, leaving terminal moraines across the US Midwest well beyond Chicago along what is now Interstate 80 from Nebraska to Ohio. What is now New York City was completely buried in ice 18,000 years ago and Long Island is in fact a terminal moraine.

Western Eurasia was also covered in continental ice during the Last Glacial Maximum (LGM), though to a lesser extent probably because westerly winds were starved of moisture to build snowpack after depositing so much water over North America. An ice sheet grew from what is now the Baltic Sea to cover Scandinavia, Britain, and much of mainland western Europe. Sea levels were hundreds of feet lower than today, with North America connected to Asia via the Bering Land Bridge and the ice-covered British Isles fully connected to mainland Europe. The Mediterranean Sea was a freshwater lake, flowing into a much lower Atlantic Ocean via a waterfall at the Straits of Gibraltar.

It takes a long time to build continental ice sheets. The growth of ice sheets is limited by the supply of water from precipitation. Given today's annual rain and snowfall in central Canada (from where the Laurentide Ice Sheet grew), it would take 40,000 winters to accumulate enough snow to build an ice sheet 1000 meters thick. During colder glacial times the climate was almost certainly drier so this estimate is just a lower bound for how long it must take to grow an ice sheet that covers Canada.

By contrast melting an ice sheet can be much faster because it's not water limited. All it takes is lots of summer sunshine. Bubbles in ice cores and fossils in ocean cores show that Ice Age cycles are very asymmetric, with each 100,000 year glacial cycle comprised of about 90,000 years of gradual cooling followed by 10,000 years of rapid warming. This asymmetry reflects the contrast between the slow water-limited growth of ice sheets and their much faster sunlight-limited melting. Slow ice accumulation and fast melting accounts for the characteristic "saw-tooth" asymmetry of Ice Age cycles as revealed in paleoclimate records. Note the similarity of the asymmetric Ice Age cycles with the asymmetric seasonal cycles of snowpack accumulation and melting at my mountain cabin!

5.3.3 Orbital Timing of Ice Ages

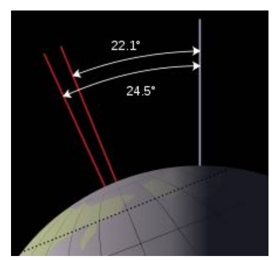


In the early 20th Century, a Serbian mathematician named Milutin Milankovitch developed a detailed theory that explained the timing of Ice Ages based on periodic fluctuations in the geometry of Earth's orbit around the Sun as it's perturbed by the gravity of the rest of the planets. At the time there was no quantitative data about ice age timing against which the Milankovitch theory could be tested so it fell out of favor for decades. But beginning with the stable isotope analysis of deep-sea cores in the1970s the theory was found to explain much of the variability in the data. So-called "***Milankovitch cycles***" are now widely accepted as an explanation of Ice Age timing.

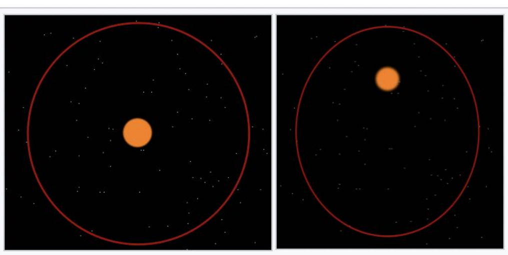
Milankovitch cycles involve three fundamental changes in Earth's orbit that interact with one another to change the distribution of solar radiation by season and latitude. It's important to note that these changes barely affect the total amount of sunlight reaching our planet in a year. Rather, by changing the relative strengths of seasons in different latitudes, they impact the growth and melting of continental ice by modulating the amount of summer sunshine available to melt winter snows.

The ***three Milankovitch cycles involve***

1) the ***tilt*** (sometimes called "obliquity") of Earth's axis;
2) the ***eccentricity*** (ellipticity, roundness) of Earth's orbit; and
3) the ***timing*** ("precession") of the seasons relative to the distance to the Sun.



The ***tilt*** of Earth's rotational axis is of course "the reason for the seasons." When the north pole faces the Sun we have long days and the Sun is high in the sky. We call this "summer." Conversely when our end of the world points into the outer dark we have short days with low Sun and it gets very cold. We call that winter. Of course, our winters are summers in Australia and vice versa. The tilt of the Earth's axis varies from about 22.1º to 24.5º relative to the plane of our orbit around the Sun in a timescale of about 41,000 years. ***When the axis is tilted more strongly the seasons are more extreme and vice versa***.

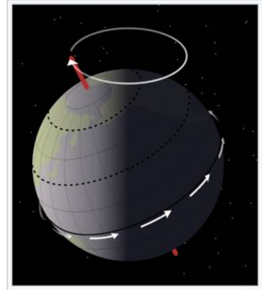


Circular orbit, no eccentricity

Orbit with 0.5 eccentricity, exaggerated for illustration; Earth's orbit is only slightly eccentric

The ***eccentricity*** of Earth's orbit measures how far "out of round" it is. Planets don't orbit in perfect circles. During part of the year we are slightly closer to the Sun than average and vice versa. Earth's orbit cycles from being elliptical in one direction to being more circular, then more elliptical in the opposite direction and back again in response to gravitational pushes and pulls of the other planets. These cycles take about 100,000 years to repeat. ***When Earth's orbit is more elliptical, the changing distance to the Sun can make seasons stronger or weaker.***

The Earth's rotational axis also swings around slowly in a big circle, pointing the north pole toward different points in the sky. This precession of the axis is precisely analogous to a spinning top wobbling around on a table, and in Earth's case takes 26,000 years to come around each time. Precession has the effect of moving the seasons around to different parts of our orbit, which modulates the relative timing of the Earth-Sun distance and the occurrence of northern summer. ***When northern summer coincides with Earth's closest pass to the Sun, our summers are hotter whereas summers in Antarctica are colder and vice versa.***



Axial precessional movement.

Recall that none of these orbital cycles has much effect on the total amount of sunlight reaching the Earth. When summers are hot in Siberia, they are cold in Australia. How then, do these cycles produce such profound changes in climate and cause miles-thick ice sheets to advance thousands of miles across the northern continents and then retreat again, every 100,000 years?

It turns out that summer on the northern continents are the key. Continental ice sheets require, well, continents! At 60 ºN latitude there is almost no ocean whereas at 65 ºS latitude there is no land. There *can't* be continental ice sheets at 65 ºS and there is *always* a continental ice sheet from 70 ºS to the South Pole. No amount of summer sunshine can make ice sheets at 65 ºS and no amount of summer sunshine can melt ice sheets further south.

Think of the Milankovitch orbital cycles like musical rhythms that beat together. The three frequencies (26,000 years for precession, 41,000 years for tilt, and 100,000 years for eccentricity) interact to modulate the distribution of sunlight by season and latitude everywhere. But the only part of these variations that counts for the growth and loss of continental ice is the changes in summer sunshine at 65 ºN.

When the three Milankovitch cycles conspire to make Canadian (and Siberian) summers hot, ice melts. When they conspire to make Siberian (and Canadian) summers cold, ice grows. These changes are then amplified by the positive feedback with albedo and with water vapor to produce global warming and cooling. Ultimately these forcings and feedbacks produce the roughly 100,000 year cycles of Ice Ages because it takes about that long to build continental ice sheets and then melt them again (Fig 5-15 below).

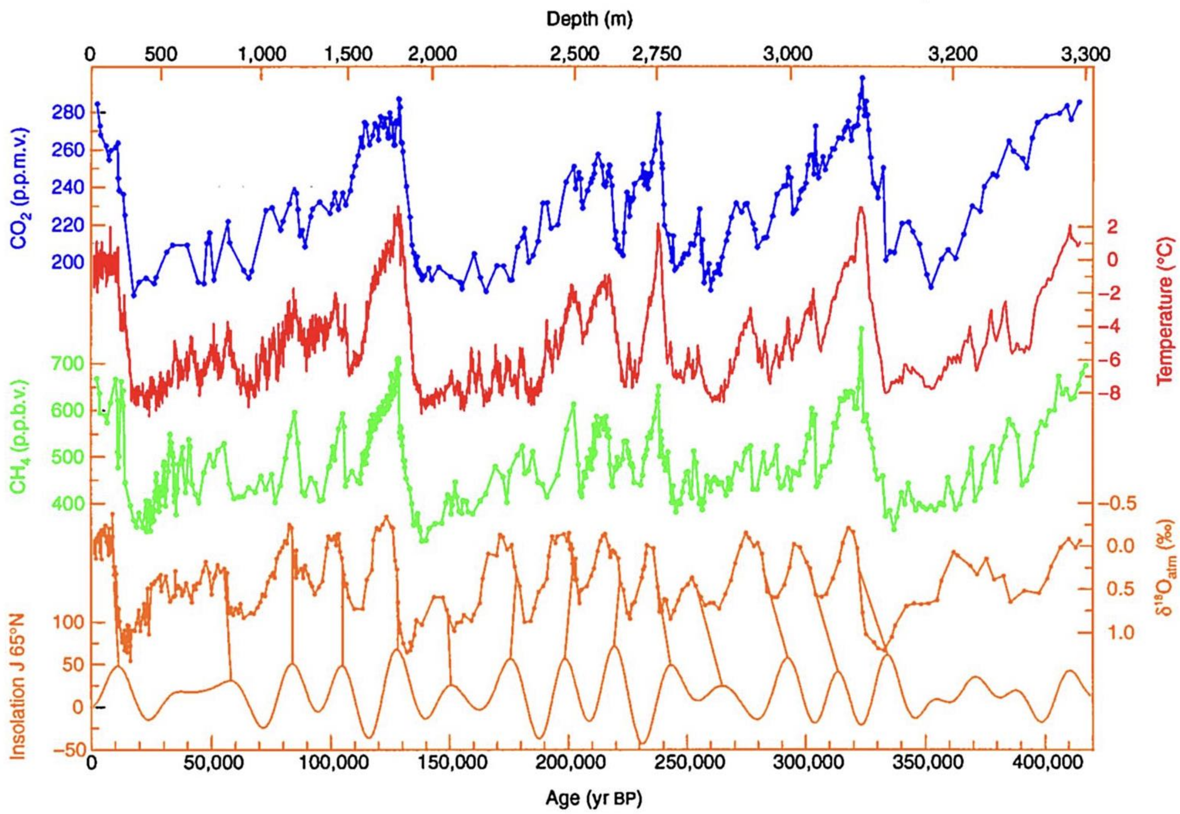


Figure 5-16: Variations in concentrations of CO_2 (blue), temperature (red), methane (green), global ice volume labeled d18O in orange), and summer sunshine at 65N (insolation in orange) over the past 420,000 years reconstructed from analysis of icee cores retrieved from Antarctica. Wikimedia Commons.

5.3.4 Since the Last Glacial Maximum

Following the Last Glacial maximum (LGM) 18,0000 years ago, climate warmed rapidly and ice retreated worldwide over the next 10,0000 years, reaching essentially its modern limits in Greenland and Antarctica by 8,000 years ago. Global average temperature rose about 5 Celsius over this period (0.05 Celsius per century) and sea levels rose 120 meters (about 400 feet), sundering Asia from North America and Britain from Europe. Vegetation gradually spread northward and upward into previously ice-covered mountain ranges.

About 14,000 years ago sea level rise abruptly accelerated (Fig 5-16) as the Laurentide Ice Sheet in North America collapsed. As water poured off the land and into the oceans, sea levels rose about 30 meters (100 feet) in 400 years. Think about sea levels in Florida or Louisiana rising 30 inches every decade for centuries! It took 4000 years of global warming at 0.05 Celsius

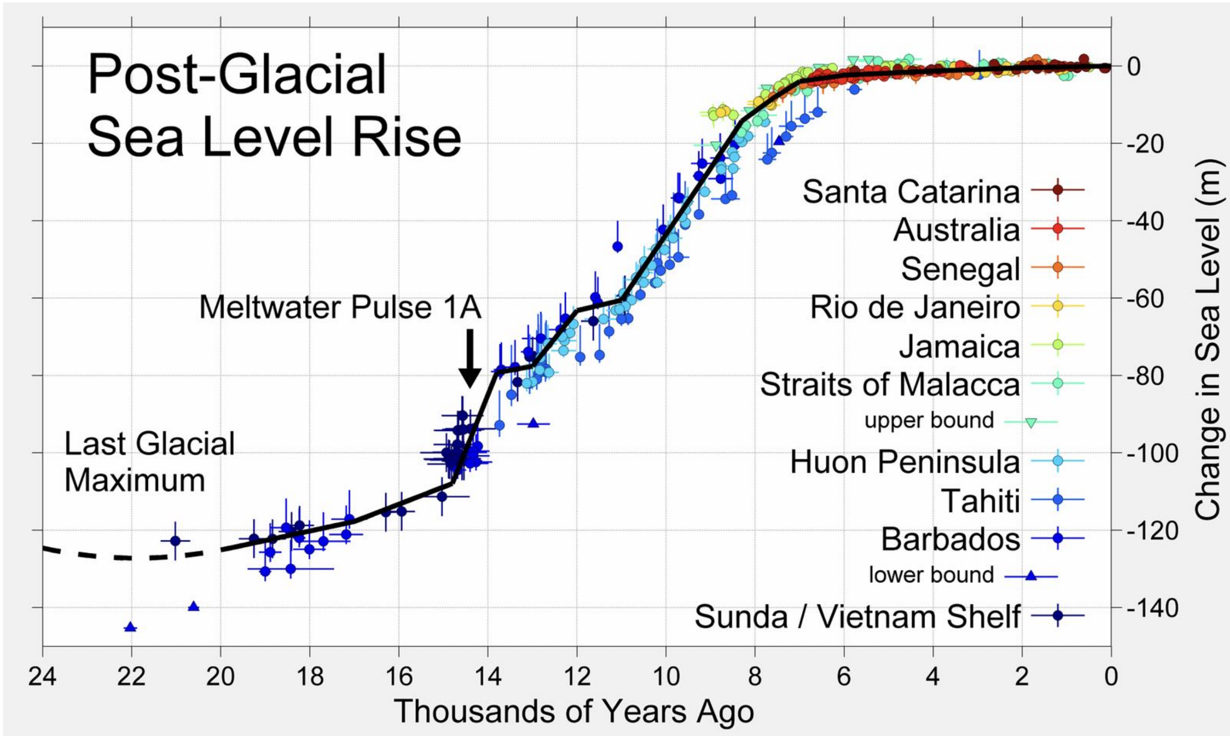


Figure 5-17: Sea level rise during deglaciation following the Last Glacial Maximum

per century to trigger that collapse but remember our climate has warmed more than 1 Celsius in the past century alone.

Post-glacial global warming reached a "climatic optimum" around 8,000 years ago (6000 BCE) at about the time summer sunshine at 65 ºN peaked Fig 5-17 below). Intensive Milankovitch forcing of sunshine at 65 ºN has been declining ever since but CO_2 started to slowly rise with the beginning of deforestation for intensive agriculture in several centers of early human civilization. Global temperatures fell until fossil fuel combustion began with the Industrial Revolution around 1800. Rapid warming since that time has now reversed the Milankovitch-forced cooling and global temperatures are now probably higher than they've been since the last interglacial period 125,000 years ago. Meanwhile CO_2 concentrations have reached 420 ppm, the highest since before Pleistocene Ice Ages began millions of years ago.

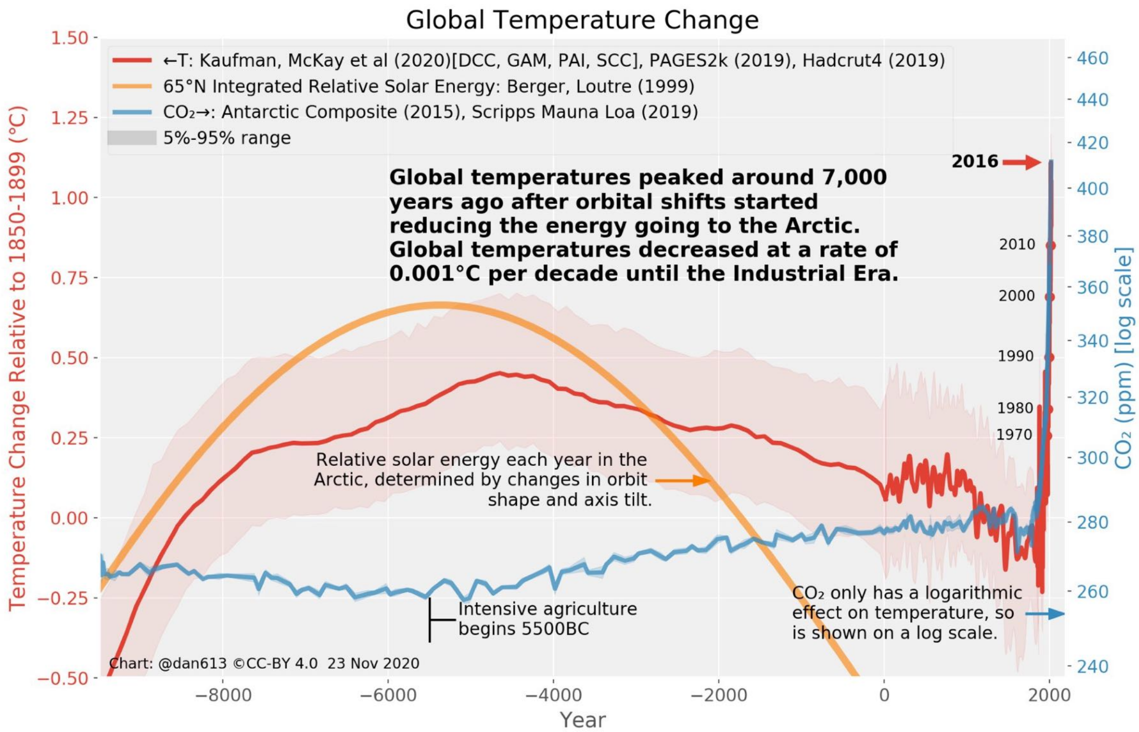


Figure 5-18: Sunshine at 65 N (yellow), atmospheric CO2 (blue), and global average temperature (red) over the past 12,000 years. Chart credit @dan613, Creative Commons license