PALEOCLIMATOLOGY: HOW WE KNOW EARTH'S CLIMATE HISTORY

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Despite a wealth of data indicating that the current rate of climate change is greater than at almost any time in recent Earth history, a lack of knowledge about Earth's natural climate variability is fueling climate change skepticism. This paper outlines the major factors controlling Earth's climate, how paleoclimate proxy records are employed to understand past climate, and why the current rate of climate change is alarming. Using five graphs that display paleoclimate proxies over a range of time scales, from billions to thousands of years, the current trend of increasing temperature and is examined in light of what we have learned from the past.

INTRODUCTION

Earth scientists have long been fascinated with how Earth's climate has changed over its ~4.55 billion year history – from periods when vast expanses of the Earth's surface have been frozen, to times when it has been ice free and far warmer than today. Currently, a worldwide network of climate stations, satellites, ships, marine mooring stations and autonomous floats collect climate data using state-of-the-art instruments. These data are synthesized into a global picture of current trends using sophisticated statistical and modeling approaches. Using a variety of independent methods, laboratory groups around the world reach the same conclusion, the Earth is currently warming at a rapid rate. Why this rate is alarming requires understanding of how climate has varied in the past, before the advent of humans influence on climate. The modern instrumental record of climate data only stretches back so far. While local measurements of climate variables like temperature and precipitation date back hundreds of years, and principally so in Europe and East Asia, data sufficient to calculate global averages have only been available from about 1880 on. So how do scientists study past climate, or paleoclimate, without the use of modern instruments, and how is current climate warming evaluated in the context of the past?

To understand the variability in the Earth's climate system over longer time scales, scientists develop new ways to extend the instrumental record. They look for measurable chemical, physical and biological factors in the natural environment that respond to changing climate and can be used to constrain change in the past. Luckily, a wealth of paleoclimate clues are recorded in phenomena such as tree rings, air bubbles in polar ice sheets, microfossils in seafloor sediments and organic deposits in lakes and rivers. In fact this work, the field of paleoclimatology, is essential to distinguish the contributions by humans from those driven by Earth's natural climate system.

PALEOCLIMATOLOGY

Paleoclimatology, the study of past climate, helps us answer important questions about climate dynamics. How does climate vary naturally, that is without human influence? What variations in the Earth system force climate to change and what is the role of feedbacks in this system? What are the rates of these natural changes? Is there potential for "climate surprises", that is abrupt changes to the Earth's climate system? To answer these questions, paleoclimatologists use "proxies".

A paleoclimate proxy is a preserved physical, chemical or biological characteristic of the environment that can provide constraints on climate change in the Earth's system before direct measurements were available. Proxies provide a way to estimate climate parameters like temperature, precipitation and atmospheric CO_2 concentration. The most useful paleoclimate proxies are preserved in archives – geological or biological materials that accumulate over time, providing a chronological record of the proxy. The goal for paleoclimatologists is to identify paleoclimate proxy archives that are as long, continuous, accurately datable and undisturbed as possible.

As you might expect, it is increasingly difficult to find such climate archives further back in time as their preservation potential diminishes and they are overprinted by numerous chemical, biological, and physical processes. Moreover, various proxy archives provide information on vastly different timescales, from 100s of years using archives such as tree ring data to millions and even billions of years using some of Earth's most ancient rocks. There are many different types of climate proxy data and a wide variety of different archives. Multiple proxies are often used in concert to increase the reliability of measures of past climate and proxy data are typically calibrated against modern instrumental data to yield a more quantitative reconstruction of climate variability in the past. Figure 1 shows examples of some of the most common climate proxy data archives, each of which is described briefly below.

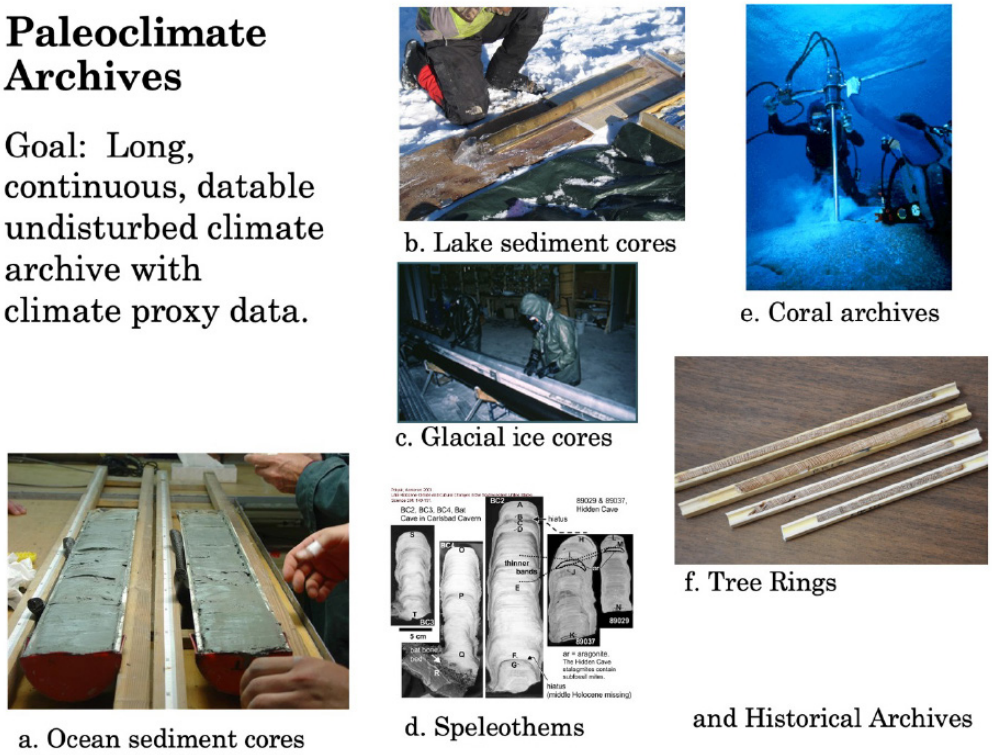


Fig. 1. Examples of paleoclimate archives that contain proxies used to estimate past climate conditions. a) Photo from The Exploratorium Ice Stories blog; b) Photo courtesy of the Montana State University Paleoecology Lab. c) Photo by Kendrick Taylor, Desert Research Institute (image courtesy of the NOAA Image Gallery); d) Polyak and Asmerom, Science 05 Oct 2001; e) Photo by Maris Kazmers (courtesy of the NOAA Image Gallery).

f) Photo credit Jon Theisen, Wooster Geologists Blog

Ocean sediment cores: Core samples taken from the seafloor are robust archives of past climate. They are relatively long and continuous, and as a result of decades of deep sea drilling and coring activities, they have been recovered across the global ocean floor and record many tens of millions of years of Earth history. Encased in the sediment are remains of microfossils such as foraminifera, a type of single-celled planktonic or benthic organism with a calcium carbonate shell the size of a grain of sand. The isotopic chemistry of these shells yields a measure of the seawater's temperature and chemistry at the time the shell formed. Deep sea sediment cores can also be reliably dated.

Lake sediment cores: Ancient grains of pollen that were swept, blown or otherwise accumulated in lake sediments provide a picture of Earth's past vegetation. By revealing the type of plants growing at that time, pollen provides a picture of a past world through the vegetation that climate supported. Lake sediment cores aren't typically as long as deep sea cores, but they can be continuous and provide high resolution data, especially in the more recent past (~10,000 year time frame).

Ice cores: Extracted from ancient continental ice sheets and glaciers, ice cores have distinct annual layers and contain tiny bubbles of ancient air. Each bubble is a microscopic time capsule that reveals how much carbon dioxide, methane and other gases were in the atmosphere at the time the ice formed and trapped the gases. The isotopic composition of oxygen in the ice itself also provides a proxy record of local temperature. Ice cores are in essence a vertical timeline of past climates dating back hundreds of thousands of years.

Speleothems: Speleothems are mineral deposits formed from the seepage of groundwater into underground caverns. Stalagmites, stalactites and other concretions often have annual layers or contain compounds that can be radiometrically dated. The thickness of mineral layers and isotopic analyses can be used to determine past surface climate conditions, specifically the local temperature and precipitation history.

Coral skeletons: Much like trees, corals lay down layers in their skeletons that hold important climate data. Corals form a calcium carbonate-based skeleton, extracting the elements that make up that structure from seawater. This chemical composition of this corallite varies with the season and shifting ocean conditions, such as water temperature or available nutrients. Scientists extract small core samples from coral reefs and study the growth patterns and chemical composition for information about past oceanic temperature and extreme climate events such as El Niño-Southern Oscillation (ENSO).

Tree rings: Every year, a tree adds another ring to its girth and the spacing between rings provides a clue about past climates. In southern California, rainfall is the biggest contributor to a tree's growth spurts, so the varying width of rings indicates how much rain fell that year. Dry years produce narrow bands, while wet years produce wide bands. In other wetter parts of the world, the tree rings might reveal other important information. For instance, a tree ring can also contain chemical signatures that reveal how much sunlight a tree absorbed or ambient temperature changes.

Historical archives: Historical documents are another type of proxy data. Observations of weather and climate conditions recorded in ship and farmers' logs, newspapers and other written records, when properly evaluated, can provide both qualitative and quantitative information about past climate.

WHAT CAUSES CLIMATE TO CHANGE?

Deciphering the paleoclimate record requires a basic understanding of the processes that control the Earth's climate. As you might expect, it is complicated, but can be understood in a general way by understanding two main concepts – climate forcings and climate feedbacks. At the most basic level, Earth's overall temperature is determined by a balance between incoming and outgoing energy in the form of radiation (e.g., radiant energy of the electromagnetic spectrum). Anything that shifts this balance changes, or "forces", the Earth's climate to warmer or cooler conditions.

Three Factors Determine the Earth's Climate

1. The amount of incoming solar radiation
2. The albedo of the planet
3. How much greenhouse gas is in the atmosphere

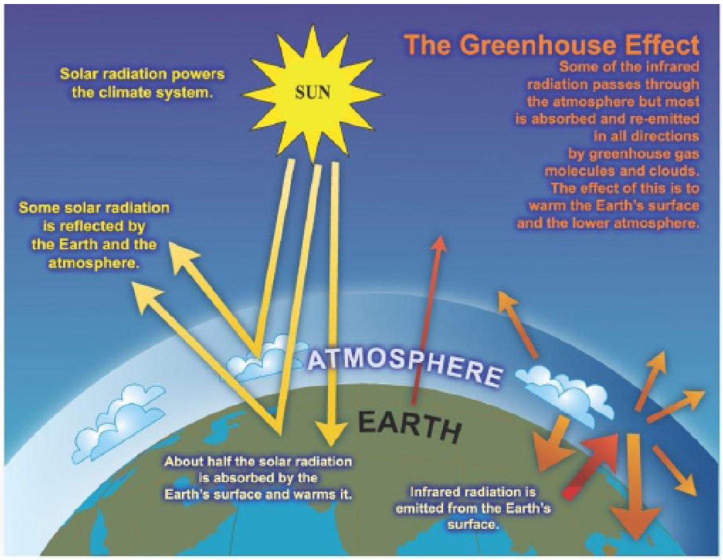


Fig. 2. IPCC AR4 WG1 FAQ 1.3 Schematic of the "greenhouse effect" illustrating the major factors controlling Earth's climate.

1. *Incoming Solar Radiation:* Electromagnetic radiation from the Sun powers Earth's climate. It is absorbed at the surface and warms the planet relative to the cold of space beyond our atmosphere. Changes in the Sun's incoming radiation, whether due to changes in the Sun's intensity or changes in Earth's orbit, change Earth's energy balance, "forcing" change in Earth's climate.

2. *Earth's Albedo:* Albedo is the Latin word for whiteness and refers to the reflectivity of a planet's surface, that is how much of the Sun's radiation is reflected directly back into space without being absorbed. White clouds and white ice reflect sunlight directly back to space, while relatively dark land and ocean surfaces tend to absorb sunlight, ultimately warming the planet. Changes in Earth's albedo shift the balance between solar radiation absorbed by the Earth and that reflected back into space without being absorbed; these changes in albedo force climate change. Black absorbs the Sun's radiation, while white reflects it, which is why we feel much hotter in black clothes than white.
3. *Greenhouse Gas in the atmosphere:* When solar radiation from the Sun is absorbed by the Earth's surface and atmosphere, Earth warms up and emits heat (thermal infrared radiation or heat energy). Thermal infrared radiation is the electromagnetic radiation detected by night vision goggles that detect heat from warm objects, like people, when there is little to no visible light. Greenhouse gases (GHG) in the atmosphere such as carbon dioxide, methane, water vapor and nitrous oxide absorb some of this radiant heat, and re-radiate it back to Earth's surface and atmosphere, in the process trapping heat at the surface much like a blanket, warming the planet. Changes in GHG concentrations change the amount of heat trapped at or near Earth's surface – increasing GHG warms the climate (a thicker blanket) and decreasing GHG cools the climate. Despite the negativity associated with GHGs in the context of climate change, it is important to realize that these gases play a key role in setting Earth's thermostat within a temperature range that makes Earth habitable. Without GHGs, the average surface temperature on Earth would be a chilly -18°C (0°F) instead of our current balmy 15°C (59°F).

Forcings are factors that shift Earth's energy balance between incoming solar radiation and outgoing thermal radiation. Feedbacks are how the Earth system responds to that change, either amplifying or diminishing the shift. One way to distinguish between the two is that forcings drive the Earth's climate system, for example changes in the Sun's irradiance, land use changes affecting the Earth's albedo (reflectivity), and burning of fossil fuels increasing greenhouse gases in the atmosphere. Feedbacks happen in response to climate forcing, for instance in a world where the addition of greenhouse gases to the atmosphere has forced warming, the albedo of the planet decreases as ice sheets and sea ice melt, exposing land and water that absorb more incoming solar radiation. This in turn drives additional warming, which gives rise to additional melting – a positive feedback.

Throughout the 4.55 billion years of Earth history, there has been a complex interplay between forcings and feedbacks, on both long and short timescales. In fact, on long timescales these factors have changed markedly and so has Earth's climate. Earth's climate varies naturally over geologic timescales and gives rise to a commonly posed question when it comes to current climate change – if climate has always been changing, even before humans inhabited the planet, why are we now worried and how do we determine whether the change is natural variability or anthropogenic forcing?

There are a lot of ways that we can answer these questions and paleoclimate provides just one avenue. The short answer is that paleoclimate data provide important perspective on how our current rate of climate change compares to the **rates of climate change** before human activity began to have an impact. By examining paleoclimate proxy data, we can observe that the rates of change in temperature and CO_2 concentrations, among other climate related variables, are generally much higher today than in the geologic past.

The remainder of this paper will navigate through five paleoclimate datasets that examine climate variability on different timescales, from thousands to billions of years; we then discuss the current climate warming trends in context of what we have learned from the past.

WHAT PALEOCLIMATOLOGY TELLS US ABOUT EARTH'S CLIMATE HISTORY IN FIVE GRAPHS

This section will review five key graphs that synthesize the most comprehensive findings of paleoclimate scientists working today. Each graph will provide a view of Earth's climate over a specific time span, starting with billions of years and ending with thousands of years. These graphs also illustrate how paleoclimatologists gather data and construct knowledge about climate in the distant past.

Three of the following data compilations are drawn from the Intergovernmental Panel on Climate Change (IPCC). This international coalition of climate scientists vet and synthesize the most robust scientific data from around the world. The IPCC reports are considered the gold standard in the climate community. These graphs are complicated, but these are the data that scientists from around the world employ to constrain past climates and inform the challenges ahead.

Taken together, these graphs tell Earth's climate story from the planet's earliest days right up to the present and provide a broad context for understanding current climate change.

Graph I: Earth's Climate Over Billions of Years

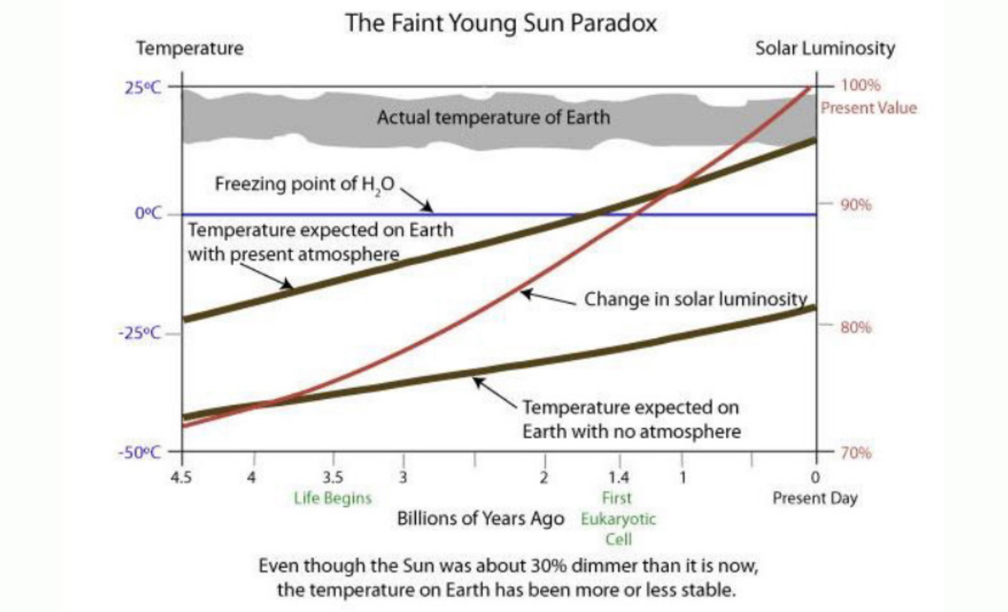


Fig. 3. Schematic of the faint young Sun paradox. Adapted from Sahni and Shtanov (2014).

Graph I splices together proxy information into a picture of what we know so far about the entirety of Earth history. Unlike the other graphs that follow, this is more of a schematic of what scientists have surmised when they survey a broad swath of Earth's climate history, especially the earliest portion. As mentioned earlier, less proxy data exist further back in time. Rocks and minerals older than 4 billion years are extremely rare due to the destructive power of plate tectonic processes. Furthermore, until life really took hold sometime after it first emerged more than 3.5 billion years ago, the organic material that often provides the chemical clues that scientists use as proxies didn't exist. However, there are small pieces of geological data that can be pieced together to infer Earth's earliest climate.

The first thing to notice in this figure is the Sun's luminosity, or brightness. If we take the luminosity to be 100% at present, then four and a half billion years ago the Sun was 30% fainter than it is today. We know that younger stars are fainter than their more mature counterparts because of observations and models of stellar evolution. Thus throughout Earth's history, the amount of incoming solar radiation has been steadily increasing. Given incoming solar radiation is one of the most important factors determining climate, this information suggests that early Earth's average temperature should have been well below the freezing point of water (the horizontal line in the schematic) with an atmosphere similar to today. Nevertheless, we know from geologic data that there was liquid water at the surface approximately two hundred million years after Earth's formation (Mojzsis et al., 2001) and that over the next 1-2 billion years, while the Sun was still relatively faint, life emerged and thrived in what paleoclimate proxies suggest was a warm liquid ocean. So even with this weaker Sun, earliest paleoclimate proxies provide evidence that the temperature on Earth was likely somewhere between 15 and 25°C. That is the paradox or puzzle – with less incoming solar radiation and with our present-day atmosphere, the average surface temperature would have been below the freezing point of water, even as recently as 2.5 billion years ago. Yet there is overwhelming evidence that this was not the case. What else could have contributed to the relatively warm and stable temperature on Earth?

First, this "paradox" remains a topic of scientific research and is not resolved in detail. Multiple, sometimes highly complex, hypotheses exist. Based on what we have presented in this paper, let's ask ourselves what else could explain the evidence that Earth was relatively warm during this time period if incoming solar radiation was so much lower. Recalling that there are two other major factors that affect climate on Earth there are two possibilities: greenhouse gasses must have been much higher, and/or the Earth's albedo must have been much lower. Let's focus on greenhouse gases, which were likely a greater factor. Estimates suggest that Earth's early atmosphere had much higher concentrations of CO_2 and other potent greenhouse gases than today. One (here simplified) hypothesis is that while sunlight was less intense early in Earth history, higher CO_2 and other greenhouse gases trapped much more of the heat generated by solar warming and kept the planet well above the freezing point of water. Given that the Sun's luminosity has increased over time, why aren't we in a raging hothouse now? Over time, the evolution of life, formation of continents by plate tectonic activity and the chemical weathering of calcium and magnesium-rich silicate rocks has led to an overall reduction in atmospheric CO_2. A balance was then established between the CO$_2$ released into the atmosphere by volcanic activity (plate tectonics) and CO$_2$ and other greenhouse gases being extracted into living material (biomass), and carbonate rocks (limestones) that store vast amounts of that early atmospheric CO$_2$. The living and solid Earth (crust and mantle) now serve as significant reservoirs of carbon that once resided in the atmosphere.

Graph II: Earth's Climate Over Hundreds of Millions of Years

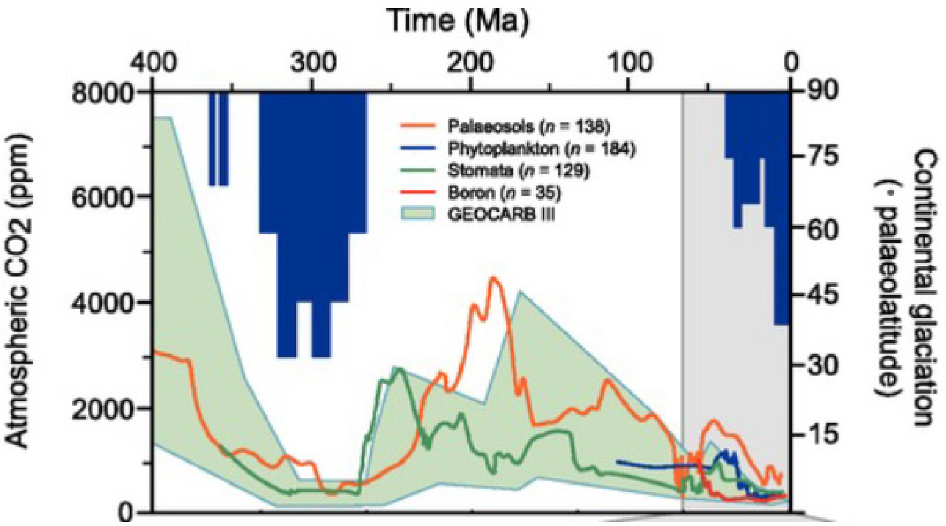


Fig. 4. IPCC FAR WG1 2007, Fig. 6.1. Atmospheric CO$_2$ and continental glaciation 400 Million years ago to present. Vertical blue bars mark the timing and palaeolatitudinal extent of ice sheets. Plotted CO$_2$ records represent five-point running averages from each of the four major proxies. Also plotted are the plausible ranges of CO$_2$ from the geochemical carbon cycle model GEOCARB III. See IPCC report and figure caption for complete description and references.

Graph II (Fig. 4) shows most of the Phanerozoic eon, which started over 500 million years ago, and spans well-known geologic eras like the Paleozoic (think earliest fish and trilobites), Mesozoic (dinosaurs of course but earliest mammals too) and Cenozoic (our current era, commonly referred to as the age of mammals). Phanerozoic literally means visible life and the beginning of this eon is the time when abundant animal and plant life began to flourish and diversify first in the ocean and then on land. Unlike the last graph, this IPCC dataset surveys a 400 million year time period when we have improved proxies for Earth's climate. These proxies might not be continuous or span the entire period, but they give a better sense of the Earth's climate system.

One of the first orders of business when studying paleoclimate is establishing whether Earth was glaciated (e.g., had permanent continental ice that did not melt over seasonal cycles) and if so how extensive that ice was. This information is garnered using a combination of geologic evidence for the presence of glaciers. The blue bars extending from the top of the graph indicate times when the Earth was glaciated and the length of those bars represents a measure of how far from the poles that glaciation extended (paleolatitude). Glacial extent is a crude representation of hot versus cold global temperatures but gives a broad sense of how Earth's climate fluctuated. Note that the present, shown on the far-right side of the diagram, is a time of permanent continental ice sheets on Antarctica and Greenland. On this time scale, we are in a comparatively cool period of Earth history.

The colored lines on this graph delineate various proxy data estimates of carbon dioxide in the atmosphere (left axis). These proxy data are not yet continuous, and not yet well constrained in time, but they are a reasonably good approximations of how CO_2 concentrations are varying across 100s of millions of years. CO_2 proxies include the size of stomata in fossil leaves, chemical signatures in soils (e.g., paleosols) and composition of photosynthetic microorganisms in the ocean (e.g., phytoplankton) as well as boron isotopic data from marine microfossils. The green shaded area represents a modeling study that examines large scale geological, chemical and biological processes that control carbon dioxide concentrations in the atmosphere and how these have changed over Earth history. All of these represent independent lines of evidence from the work of numerous different labs that have been vetted and compiled into a summary diagram by the IPCC authors.

What does PPM mean?

The acronym PPM appears regularly in paleoclimate data sets. PPM stands for parts per million. A concentration of 414 PPM CO_2 in the atmosphere indicates that out of 1,000,000 molecules of various gases in the air, 414 of those molecules are CO_2.

What do these data reveal? In general, times of higher CO_2 levels in the atmosphere correspond to times when Earth was largely ice free and by inference relatively warmer, while lower carbon dioxide levels correlate with glaciations and relatively cooler average temperatures. Glaciation on Earth appears to require lower CO_2 concentrations. Another observation is that, over most of the last 400 million years, Earth's average temperature and atmospheric CO_2 concentration were both considerably higher than they are today. We see long stretches of time on this graph when there were no permanent ice sheets and indications that CO_2 concentrations have been at times much higher than present day. Our current carbon dioxide levels today (2021) are at 414 parts per million (PPM) and rising, but this graph reveals that carbon dioxide levels may have been much greater than this, at least 1300 ppm, in Earth's warmer past.

It's important to keep in mind that the changes shown in this graph took place over hundreds of millions of years. The most likely cause for such climate variation over such a long timescale is interacting geological and biological processes. Plate tectonics results in volcanic activity that releases CO_2 from the Earth's interior into the atmosphere. The atmospheric concentration of CO_2 is then moderated by a "speed up" in the chemical weathering process of silicate rocks. In brief, atmospheric CO_2 dissolves in rainwater, making it slightly acidic, and reacts with silicate rocks. The dissolved chemical components of that weathering process (such as ions of Ca and Mg along with the CO_2) are transported to the ocean where they are incorporated into the carbonate shells of marine organisms that eventually become part of marine sediments and eventually sedimentary rocks called limestones. Such rocks provide long-term storage reservoir for a portion of Earth's carbon. Through feedbacks in the climate system over the long term, these are self-regulating processes. More CO_2 in the atmosphere triggers a warmer and wetter climate, which in turn triggers drawdown of CO_2 through the chemical weathering process, that cools the climate slowing the weathering process. So over long timescales, we see the carbon cycle at work, moving carbon in and out of the lithosphere and atmosphere and working as both a climate forcing and a climate feedback. These processes take millions of years to play out at rates that are very slow compared to the rate at which humans currently add CO_2 to the atmosphere today.

Graph III: Earth's Climate Tens of Millions of Years Ago

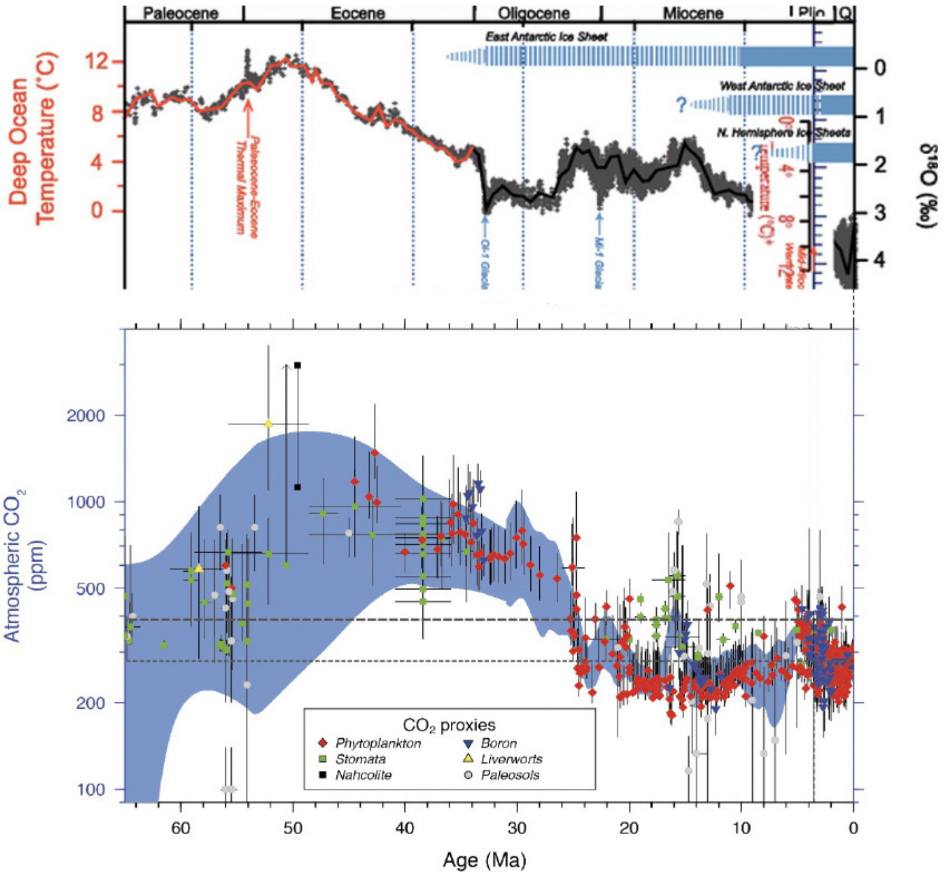


Figure 5. IPCC FAR WG1 2007, Fig. 6.1 and IPCC AR5 WG1 2013 Figure 5.2 See IPCC report and figure caption for complete description and references.

By surveying climate change on the scale of tens of millions of years we are beginning to assemble long and continuous climate proxy archives. This figure is actually two graphs and separates the proxy data for temperature (top) and CO_2 (bottom). The time period represented covers the Cenozoic, the era from 66 million years ago to today. The left hand side of the graph is the time just after the dinosaurs and many other species disappeared from the geologic record in a famous mass extinction event. On the right hand side, 0 is today and the next tick mark to the left, 2 million years ago, is the time when early members of the genus "homo" inhabited the Earth. Both of these graphs come from IPCC reports in 2007 and 2013 and use proxies for temperature and carbon dioxide — key paleoclimate indicators.

The first graph tracks deep ocean temperatures using geochemical proxies from seafloor sediment cores. Laboratories around the world have meticulously measured isotopic ratios in marine microfossils called benthic foraminifera (small single celled plankton) preserved in layers of sediment recovered from the seafloor. Foraminifera are a highly dependable paleoclimate proxy for temperatures and the marine sedimentary record provides a relatively continuous and datable archive. At fifty million years ago, the oceans were much warmer than today, followed by a long cooling trend. The blue bar at the top of the graph indicates that geological evidence of glaciers appears in Antarctica at about 35 million years ago, followed about 30 million years later by glaciation in the northern hemisphere. The bottom graph tracks carbon dioxide concentrations in the atmosphere using some of the same samples shown in the Graph II: stomata from fossilized leaves, boron, phytoplankton and soil samples. At the start of the Cenozoic era, the graph indicates that carbon dioxide concentration could have been as high as 1000 PPM, but more likely closer to 600 PPM. Just as we saw in the previous graph, the cooling over the last 35 million years corresponds with climate proxy data that indicate CO_2 was also declining. There is still a level of uncertainty surrounding these data, which is shown by the blue shaded area around the data points. As we move closer to the present-day, our confidence in the proxy-based estimates of temperature and CO_2 increases.

Graph IV: Earth's Climate One Million Years Ago

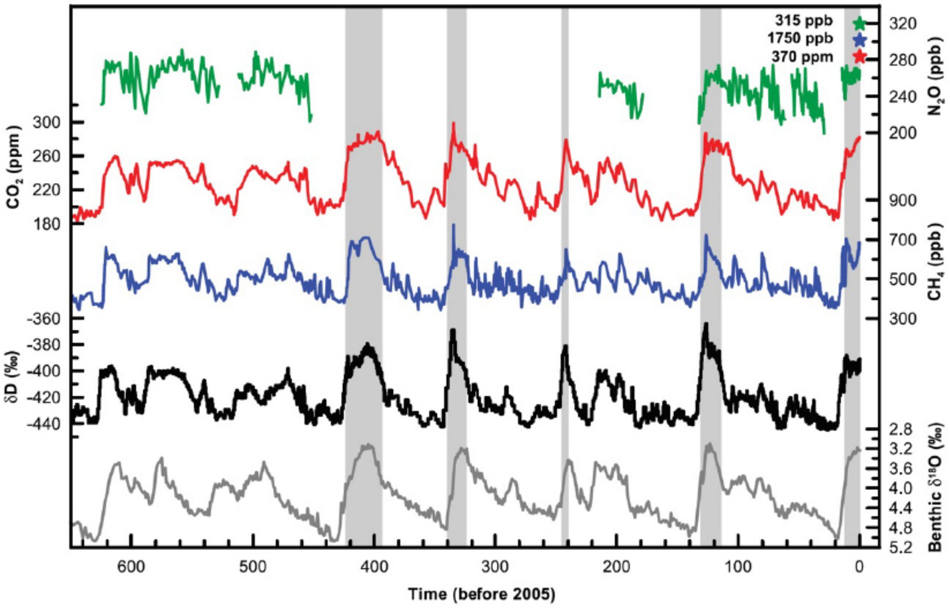


Figure 6. IPCC FAR WG1 2007 Fig. 6.4. Variations of deuterium (δD; black), a proxy for local temperature, and the atmospheric concentrations of the greenhouse gases CO_2 (red), CH4 (blue), and nitrous oxide (N2O; green) derived from air trapped within ice cores from Antarctica and from recent atmospheric measurements. The shading indicates the last interglacial warm periods. Interglacial periods also existed prior to 450 ka, but these were apparently colder than the typical interglacials of the latest Quaternary. The length of the current interglacial is not unusual in the context of the last 650 kyr. See IPCC report and figure caption for complete description and references.

There is a lot of information in this figure, but it is useful to view the various proxy data for temperature and greenhouse gasses together. This figure includes two independent sources of temperature proxy data. The bottom grey line is a high-resolution temperature proxy derived from the isotopic composition of bottom dwelling foraminifera in ocean sediments. The black line above that is temperature data for Antarctica derived from the isotopic composition of water in ice cores recovered by drilling deep into ice sheets. The ice in these cores reveals annual layers of snow deposition, making the layers easy to date, and bubbles in the ice preserve tiny samples of Antarctic air in each annual layer. The top three lines represent the greenhouse gas concentrations measured in these bubbles. CO_2 is in red, methane in blue and nitrous oxide in green. Data from ice cores is one of our most reliable proxies and have been used to reconstruct Antarctic temperatures and atmospheric CO_2 concentrations going back 800 thousand years in some of the deepest cores.

A clear pattern emerges here – the cycle between glacial and interglacial periods caused by regular, periodic variations in the Earth's orbit around the Sun and its rotation on its axis. The cycle of warming and cooling is caused by how much of the Sun's energy reaches Earth's high latitudes. This small change in incoming solar radiation is a climate "forcing" that drives these cyclic changes. These small changes are a trigger of sorts, and carbon dioxide and other greenhouse gases act as a feedback. The likely source of the GHG variations, between 180 and 280 ppm over each cycle, is likely changes in the capacity of the deep ocean to absorb CO_2, which is a function of temperature and alkalinity.

Over the last ten thousand years, the Earth has been in a relatively warm and stable interglacial period (interglacial periods are indicated by grey shading). During this time, humans established agricultural and transportation systems that define how we move and eat, and built the cities we live in. Human civilization is adapted to the stable climate we experience today.

The recent increase in atmospheric CO_2 concentration is unprecedented in this time frame. The year 2000 CO_2 concentration is 370 ppm (blue dot) and is from modern atmospheric measurements. Atmospheric CO_2 concentration surpassed 400 ppm in 2016, and the average concentration in early 2021 was more than 414 ppm. Compared to the tightly constrained range of 180 ppm (glacial) to 280 ppm (interglacial) concentrations, this level of CO_2

is higher than at any point observed for the last 800,000 years in ice core data and likely higher than any time in the last 2.5 million years (Lisiecki and Raymo, 2005)

Graph V: Earth's climate two thousand years ago

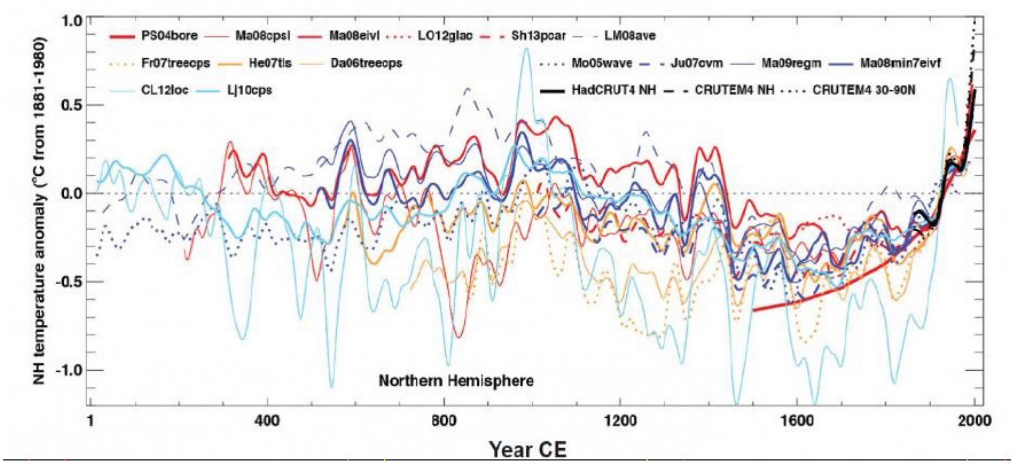


Fig. 7. IPCC AR5 WG1 2013 Fig. 5.7
See IPCC report and figure caption for complete description and references.

The last graph, Graph V, shows the last two thousand years of Earth's climate record, and includes both proxy data and direct instrumental measurements of global temperature from about 1880 to the present (far right black solid and dashed lines). Note that these data are presented as temperature "anomalies", that is a deviation from global temperature averaged over several decades, in this case from 1881-1980.

These data syntheses use a broad array of high resolution, continuous, long, datable archives including coral reefs, lake sediment, tree rings and cave rocks among others. The colored lines on this graph are the dependable proxies from numerous research groups engaged in reconstructing high resolution climate records. The wealth of proxy data available in this time frame provides a basis for comparing and statistically combining these data, including more recent data from instrumental records.

The broad trends in Graph V reveal several climatic swings in the last two thousand years of Earth's history. First, around a thousand years ago, a rise in temperatures took place in what is referred to as the Medieval Warm Period and is recorded in a number of the proxies. Following the Medieval Warm Period, a cooling period called the Little Ice Age occurred and culminated around 1600. A trend reversal begins about 1750 with the onset of the industrial revolution and temperatures start to creep up. After the 19th century, a dramatic rise in temperatures occurs leading to what was very likely the warmest 30-year period (1983 to 2012) over the last 1400 years. And the trend continues today.

CLIMATE CHANGE OVER THE INSTRUMENTAL RECORD

Looking at the last 140 years, our climate is currently warming. Figure 8 is a plot of annual globally averaged temperature data. The figure is provided by the US federal agency in charge of collecting and archiving weather, climate and oceanographic data, the National Oceanic and Atmospheric Administration (NOAA), and the National Centers for Environmental Information (NCEI). These data show that the last 7 years have been the warmest on record. The graph also shows that each of the last 4 decades has been warmer than the preceding one. The data are plotted as anomalies which are differences from an average temperature. That average is typically calculated over multiple decades, in this case for the entire 20th century (1900-1999).

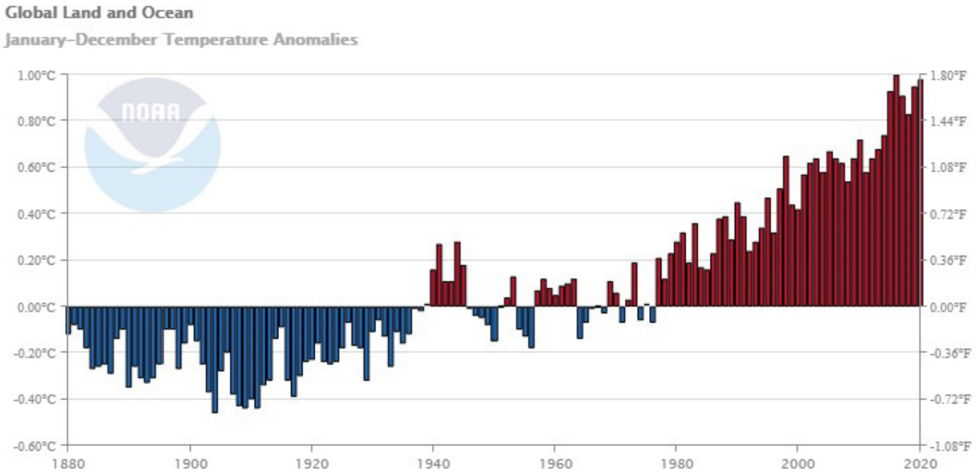


Fig. 8. Annual global temperature differences relative to the average temperature for the 20th century. Average annual global temperature for the 20th century (1900 to 1999) is represented by the 0° horizontal line on the graph. Blue bars represent annual temperatures cooler than that average and red bars indicate temperatures warmer than average. 2011–2020 was the warmest decade on record for the globe, with a surface global temperature of +0.82°C (+1.48°F) above the 20th century average. This surpassed the previous decadal record (2001–2010) value of +0.62°C (+1.12°F). https://www.ncdc.noaa.gov/sotc/global/202013

This is the historical record of climate change. These data allow us to calculate a rate of warming based on the instrumental record and compare that to what we can learn about natural variability from paleoclimate archives.

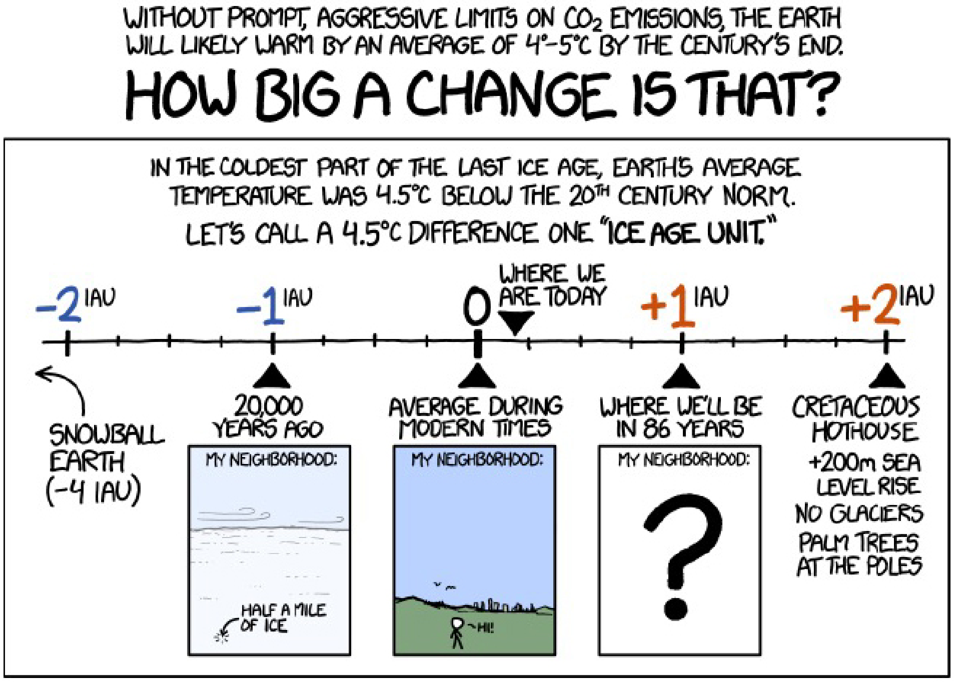
WHY ARE WE WORRIED NOW?

The paleoclimate record shows that Earth's climate has varied over its 4.55 billion year history, moving between extremes that far exceed the changes we are observing today. So why are we now worried? Over the last several decades, changes are taking place at a much faster rate than we have observed in the past. Earth's climate does have natural variability. For example, the transitions between glacial and interglacial cycles over the last million years (seen in proxy data) are sudden in a geologic sense (i.e., they take place over several thousand years), but the rate of these changes is slow relative to those we observe in the recent instrumental record of temperature and CO_2. A long-term coupling of CO_2 and temperature is observed throughout Earth's history. CO_2 and greenhouse gases are one of the three major forcing mechanisms for climate change. What we're doing now is forcing the climate by adding greenhouse gases to the atmosphere at an alarming rate and what we are now observing is an attendant relatively rapid increase in global temperature.

Another reason we are worried now is that humans are potentially at risk. Most of human civilization, including many of the things we take for granted such as agricultural and transportation systems, have been developed in the last 10,000 years, and that's a time when our climate has been relatively warm and comparatively stable. When we look at changing climate and say, "Oh, well, climate has always changed," we are ignoring the fact that it hasn't changed substantially on modern human timescales. Furthermore, humankind has never been so obviously vulnerable to climate change because of climate change threats to the natural ecosystems and built infrastructure upon which we all depend. An unusually rapid rate of change coupled with humankind's vulnerability makes us worried about climate change's impacts on civilization as we know it today.

Why is it our fault? It's our fault because human activities, such as burning fossil fuels, cement production and land use changes (e.g., deforestation) are unequivocally forcing the climate to change and the attendant feedbacks may further increase the rates of change. We know how CO_2 reacts in the climate system and we know that we are increasing CO_2 concentrations faster than any time in the past based on the proxy data. Therefore, we can confidently attribute the majority of the climate forcing that we observe now, to human activities.

Graph VI: A Bonus Graph to Sum Everything Up



Now to put all five graphs in context, let's examine this image from the scientific comic strip XKCD. In this cartoon, one "ice age unit" is equivalent to 4.5°C temperature change between the last glacial maximum at 20,000 years ago and global temperature during modern times (pre-industrial revolution). As the comic illustrates, our current trajectory projects to an equivalent warming of 4.5°C within the coming 86 years — a pace that would equal about 20,000 years of natural climate change. This is an unprecedented rate that will endanger the world we've developed and adapted to over the last two millennia. Some of the warmer time periods in Earth's early history, when there were no permanent glaciers, palm trees and other tropical species thrived near the poles and sea levels were much higher, could conceivably be the climate of the future.

The paleoclimate record shows that long term forcing of climate change from natural Earth processes have shaped the planet's climate over millions of years. It also shows that the collective actions of billions of humans can force the climate to change in a matter of decades. Climate change skepticism is often rooted in a flawed understanding of paleoclimates. The lesson to draw from all the environmental proxies is that the breakneck pace of climate change today is unnatural – as well as an imminent threat to human society. And yet, this can be a hopeful lesson, too. Recognizing that today's climate change is caused by humanity means that we can apply the human ingenuity that produced modern civilization to mitigating and adapting to climate warming.

REFERENCES CITED

IPCC, 2007: Climate Change 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp. IPCC AR5 WG1 2013 Chapter 5

IPCC, 2013: *Climate Change 2013. The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp.

Lisiecki, Lorraine E., and Maureen E. Raymo. "A Pliocene Pleistocene stack of 57 globally distributed benthic δ18O records." *Paleoceanography* 20.1 (2005).

NOAA National Centers for Environmental Information.
https://www.ncdc.noaa.gov/sotc/global/202013

Polyak, Victor J., and Yemane Asmerom. "Late Holocene climate and cultural changes in the southwestern United States." Science 294.5540 (2001): 148-151.

Sahni, Varun, and Yuri Shtanov. "Can a variable gravitational constant resolve the faint young Sun paradox?." *International Journal of Modern Physics D* 23.12 (2014): 1442018.

XKCD How Big a Change is That? https://xkcd.com/1379/

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