Arcs of Climate

Harlan Gilbert

One of the best aids to understanding the climate of the present day and to predicting its future is an examination of its past. In the following, I will examine how changes in climate appear over a variety of timescales. I hope that my readers will be as illumined—and startled—as I was by the diverse images these present, for the particular timescales I have chosen exhibit almost every possible gesture: chaos, near linearity, periodicity, equilibrium, and, of course, at the finest grain, the exponential warming of the present day.

It is my hope that comparing these diverse views will foster a consciousness of the complexity of climate as a dynamic system, open productive pedagogical avenues, and contribute to increased tolerance of complexity in the conversation around climate change.

Erratic Leaps

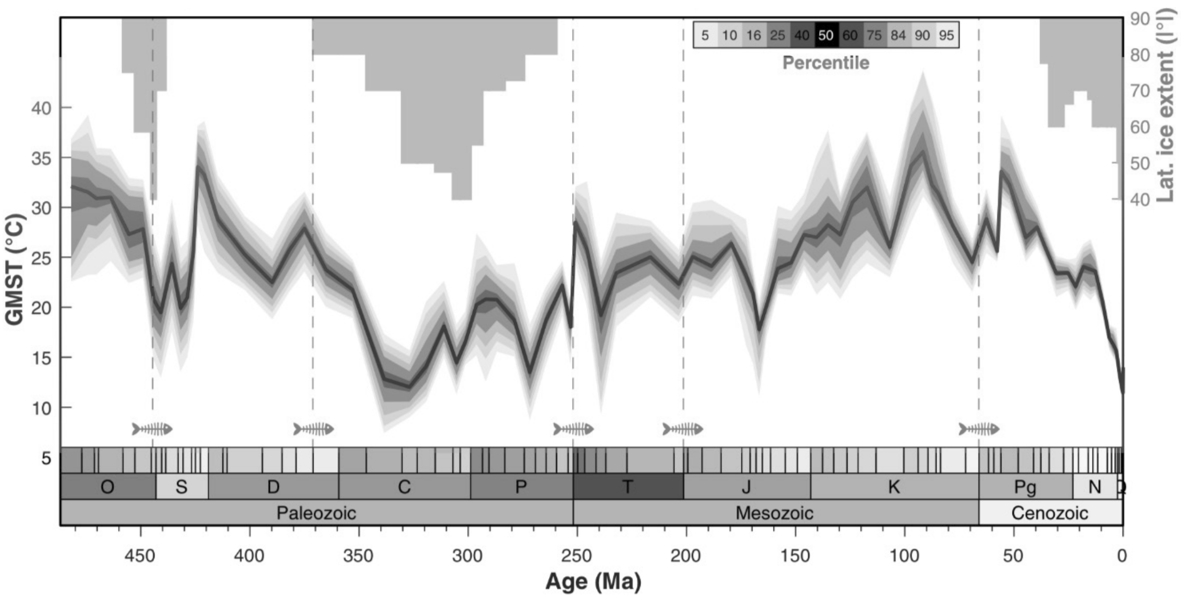


Figure 1: Temperature variations over the last half-billion years (shaded areas indicate uncertainty ranges)

In the above reconstruction of climate over nearly a tenth of the Earth's lifetime (Figure 1),[1] we see the Earth's surface temperature repeatedly undergoing dramatic and seemingly chaotic swings. At the hottest periods, temperatures averaged a remarkable 36°C (97°F) and even polar land was thickly forested, while the coldest periods saw temperatures close to those of the present day, with widespread glaciation.

Earth has been called a Goldilocks planet, referring to its conditions being "just right"—for example, neither too hot nor too cold—for life in general and for human life in particular. A comparison to the nearest planets of our solar system brings our good fortune vividly home: on Venus, water can only exist as steam, due to its average temperature of 464°C/867°F,[2] while on Mars, as the average temperature is -65°C/-85°F, water can only appear as ice.

There were even long-ago periods when the Earth's surface was entirely or nearly entirely covered with

1 Credit: Emily J. Judd et al., "A 485-Million-Year History of Earth's Surface Temperature," *Science* 385, no. 6715 (September 20, 2024): eadk3705, https://doi.org/10.1126/science.adk3705.
The darkened areas at the top of Figure 1 show the furthest latitude reached by glaciers.

2 It also rains sulfuric acid on Venus, so… less than ideal conditions.

ice. Each time such "Snowball Earth" conditions recur, only the simplest sea organisms survive. Fortunately, Snowball Earth conditions have not been seen for many hundreds of millions of years, and we can be grateful that for the last half-a-billion years, despite the apparent chaos, our planet's climate has stayed within quite favorable limits, providing a beneficent environment for the evolution of ever-more-complex life.

While many of the erratic shifts visible in Figure 1 were driven by singular events—enormous volcanic eruptions, powerful meteor impacts, major changes in plate tectonics, and shifting astronomical influences—others arose as part of the naturally chaotic progression typical of complex dynamical systems,[3] an erraticism familiar to us over shorter time frames in surprising weather events and unpredictable yearly variations. Should such very large swings in temperature recur—and there is no reason to suppose that either singular external events or internal dynamic swings are any less likely now than in the past—this would be devastating to vast swaths of life on Earth, and, of course, to human civilization in much or all of the planet.

To summarize: Though the climate remains vulnerable to unexpected twists and turns, we can be grateful that for the last half-a-billion years, Earth has really been an ideal environment for the evolution of complex land organisms: amphibians, reptiles, birds, mammals, and that most special mammal, human beings.

Dramatic Cooling

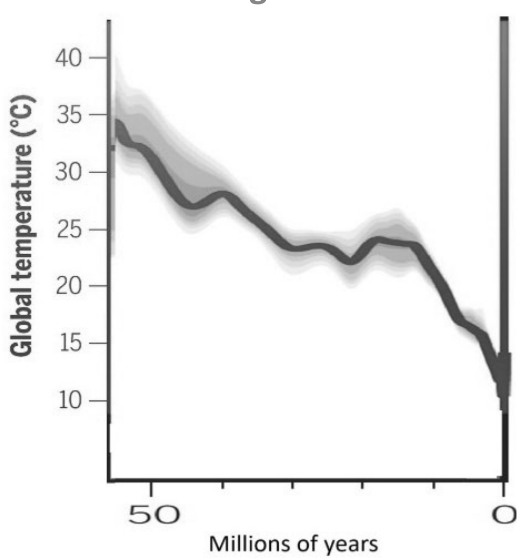


Figure 2: The cooling trend of the last 50 million years

Surprisingly, over a shorter timeframe, climate's evolution tells a radically different story: for more than 50-million years, Earth's temperature has been on a long, slow decline (Figure 2). In the course of this long, sustained fall, global temperatures reached some of the coolest conditions seen in nearly half-a-billion years (Figure 1), having dropped a remarkable 20° C/36° F. Just imagine if the Earth's temperature were that much hotter today—and every day!

Nearly all of the fish, birds, and mammals familiar to us today evolved under these relatively cool temperatures.

This cooling correlated with and is thought to be the result of a dramatic tenfold drop in carbon-dioxide levels.[4] Exactly why this dramatic drop occurred is somewhat speculative, but factors may have included geological weathering and interactions of the tectonic plates that increased the absorption of carbon-dioxide and changes in ocean currents that stimulated the growth of carbon-dioxide consuming plankton.

The initial cooling allowed the formation of a permanent ice sheet in Antarctica, the beginning of the *Late Cenozoic Ice Age,* 34 million years ago. As ice reflects most of the sunlight striking it, its formation tends to cool the planet further, which in turn leads to more ice forming, which in turn leads to further cooling. This positive feedback loop had further cooled the Earth sufficiently for glaciers to begin forming beyond the South Pole some 2½ million years ago. The *Quaternary Glaciation* had begun.[5]

To summarize: At this scale, the chaotic development characteristic of the longer-term picture is no longer in the foreground. Instead, we see initial cooling starting a feedback loop that lasted 50 million years, with any occasional rise remaining both slight and brief before the relentless descent in temperature continued. As a result, we, and the flora and fauna around us, are adapted to a relatively cool Earth.

Cyclic Glaciation

In surprising contrast to the chaos and continual descent seen dominating the first two timespans, over the last million years, the Earth's climate has cycled periodically in a roughly hundred-thousand-year rhythm, while temperatures remained within a fairly narrow range (Figure 3).[6]

3 E. N. Lorenz, "Can Chaos and Intransitivity Lead to Interannual Variability?," *Tellus A* 42, no. 3 (1990): 378–89, https://doi.org/10.1034/j.1600-0870.1990.t01-2-00005.x.

4 William H. Menke, "What Geology Has to Say About Global Warming – State of the Planet," July 11, 2014, https://news.climate.columbia.edu/2014/07/11/what-geology-has-to-say-about-global-warming/.

5 We are thus living in the Quaternary intensification of the larger Late Cenozoic Ice Age.

6 Only part of this cyclic glaciation is shown in Figure 3; it extended more than a million years.

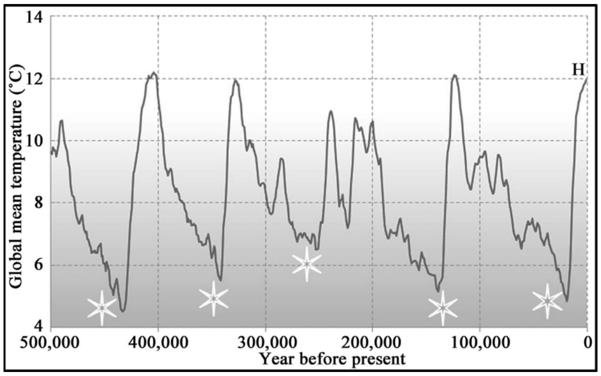


Figure 3 Rhythmic temperature variation over the last 500,000 years

During each cooling phase, the glaciers dramatically advanced, as temperatures dipped well below even the coldest averages seen in Figure 1. Most of northern North America, Europe, and Asia, constituting a quarter of the land surface, was enduringly frozen over as recently as 20-thousand years ago. During each warming phase, the glaciers retreated again but did not disappear.

A million years of humanity's development has taken place against the background of this rhythmically cycling climate. That *Homo sapiens* (as well as its predecessors and relatives) repeatedly dealt with cooler and warmer temperatures and advancing and retreating ice must have stimulated considerable lifestyle flexibility. Nevertheless, the variations in temperature and ice-cover over this period were quite moderate compared to the Earth's earlier swings in temperature and ice cover: no more Snowball Earths, no more tropical forests at the poles.

The early climatologist Milutin Milanković showed that this roughly 100,000-year cycle is the result of periodic variations in the axial tilt, orbital shape, and orbital orientation of the Earth. In Figure 3, it can be seen that we are now at the peak of the current Milanković cycle. Normally, a long, slow drop in temperature, accompanied by spreading glaciation, would follow.

How soon should we expect this? No one quite knows: current projections of the onset of the next cooling period vary between one- and 50-thousand years![7] This is because the factors that drive the Milanković cycles interact with each other, as well as with many other influences, in quite complex ways. These estimates may be irrelevant, in any case, as at current greenhouse gas levels, a Milanković cooling cycle is unlikely to begin.[8]

Summary: The climate has been cycling quite regularly over a moderate range of temperatures for the last million years. Though astronomical factors will eventually tend to induce cooling, it is not known when this will begin, and greenhouse gases at current levels would likely counteract this influence.

Stability

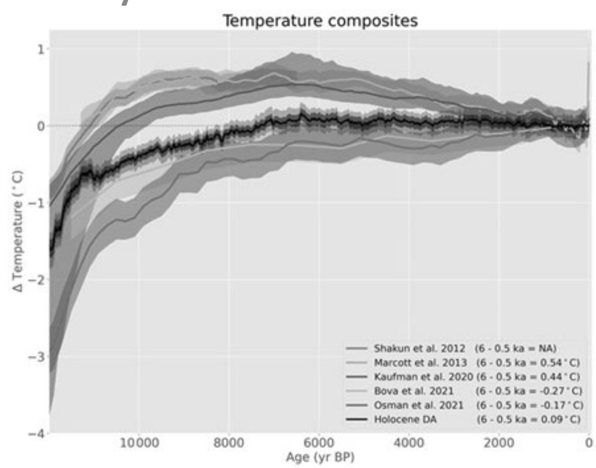


Figure 4: The remarkable stability of the Holocene era climate

The Earth's average temperature has remained within a remarkably uniform range over the last ten-thousand years (see Figure 4).[9] This era of climatic stability has seen incredible changes to human civilization involving radical lifestyle transformations, including:

- the rise of agriculture, the domestication of animals, and a widespread transition from nomadic to settled populations;
- the invention of writing, allowing greater transmission of culture between cultures and generations; and
- vast and extraordinary advances in arts, crafts, and technology.

Intriguingly, this period of quite stable climate conditions encompasses the entirety of recorded history. As we know very little of what human life was like when the climate was less stable, our expectations have solidified around this moderate climate regime. Yet, this stability is unusual and remains fragilely vulnerable

7 The high end projection is from A. Ganopolski, R. Winkelmann, and H. J. Schellnhuber, "Critical Insolation–CO2 Relation for Diagnosing Past and Future Glacial Inception," Nature 529, no. 7585 (January 2016): 200–203, https://doi.org/10.1038/nature16494.

8 Richard Black, "Carbon Emissions 'Will Defer Ice Age,'" BBC News, January 9, 2012, sec. Science & Environment, https://www.bbc.com/news/science-environment-16439807.

9 The various colors seen in this figure show reconstructions based on different phenomena (e.g. the composition of seashells or ice-core data).

not only to all the influences mentioned above—erratic events, long-term trends, cyclic variations, but also to a new factor: anthropogenic climate change.

Exponential Rise

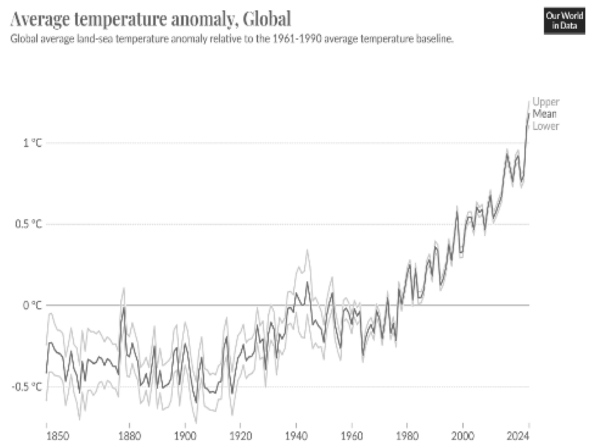


Figure 5: Rising temperatures over the Industrial Age

The stability of the Holocene climate appears to be coming to an end, as global temperatures have risen more than 1°C/2°F over the last century (Figure 5).[10] We are living through a historical first, a dramatic shift in climate whose effects can be recorded in real time: glaciers melting, reefs dying, species becoming extinct at record rates, etc.

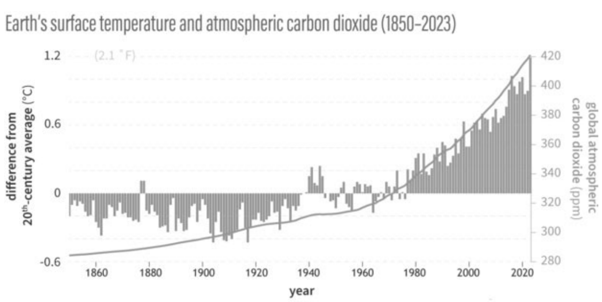


Figure 6: Temperature and carbon-dioxide levels

This rise in temperatures followed, and can with great confidence be attributed to, rising levels of greenhouse gases such as carbon-dioxide and methane (Figure 6).[11] Historically, a doubling of CO2 levels has resulted in a temperature rise of 8°C/14°F, and carbon-dioxide levels have gone up about 50% over the last 150 years.[12] The eventual effect can be expected to be far greater than anything we have yet seen, as the levels continue to rise rapidly; furthermore, temperature changes tend to follow greenhouse gas levels with a delay.[13]

In addition to this direct effect, a positive feedback loop is at work, accelerating these changes exponentially, as warming temperatures tend to release more greenhouse gases.

Summary: Temperatures are rising exponentially and will continue to do so until we tackle the enormous challenge of bringing greenhouse gases under control.

The Climate Run AMOC

At the same time, the Atlantic Meridional Ocean Conveyor, a massive flow in the North Atlantic Ocean, exerts a critical effect on the Earth's climate. By bringing warm tropical waters up to the polar regions, this current reduces glaciation in northern latitudes, with a net warming effect on Earth. The Gulf Stream is one well-known manifestation of this oceanic phenomenon.

This current has repeatedly abruptly started up or shut down in the past and is currently weakening rapidly. If it were to shut down, glaciation at the North Pole would increase, starting a feedback loop of increasing ice cover leading to cooler conditions, leading to further increases in ice cover. The Woods Hole Oceanographic Institution foresees a "potential for cooling of 3 to 5 degrees Celsius in the ocean and atmosphere should a total disruption occur…. a third to a half the temperature change experienced during major ice ages…. Global warming can induce a colder climate."[14]

The timing of the eventual tipping point that would shut down this circulation is very uncertain: estimates range from the year 2050 to 2100 and beyond.[15]

To summarize: In parallel with the warming tendency of greenhouse gases, there is the danger, at an unknown

10 Credit: Glen Fergus, Creative Commons license.
Note that in Figures 5 and 6, the temperatures are shown relative to the late twentieth-century mean, approximately 14°C/57°F, whereas the previous figures show absolute temperatures.

11 Adolf Stips et al., "On the Causal Structure between CO2 and Global Temperature," *Scientific Reports* 6, no. 1 (February 22, 2016): 21691, https://doi.org/10.1038/srep21691.

12 However, any discussion of greenhouse gases and climate change should include both the positive correlations and the problematic areas that demonstrate the limitation of our current knowledge. There have been periods when temperature and CO2 levels diverged inexplicably, as well as periods when they remained closely correlated, despite the presence of unrelated influences on climate that should have reduced this correlation significantly. Judd et al., "A 485-Million-Year History of Earth's Surface Temperature."

13 Credit: James H. Butler and Stephen K. Montzka, Creative Commons license.

14 Woods Hole Oceanographic Institution, n.d.

15 Stefan Rahmstorf, "Is the Atlantic Overturning Circulation Approaching a Tipping Point?," *Oceanography* 37, no. 3 (April 10, 2024): 16–29, https://doi.org/10.5670/oceanog.2024.501.

time in the not-too-distant future, of dramatic cooling.

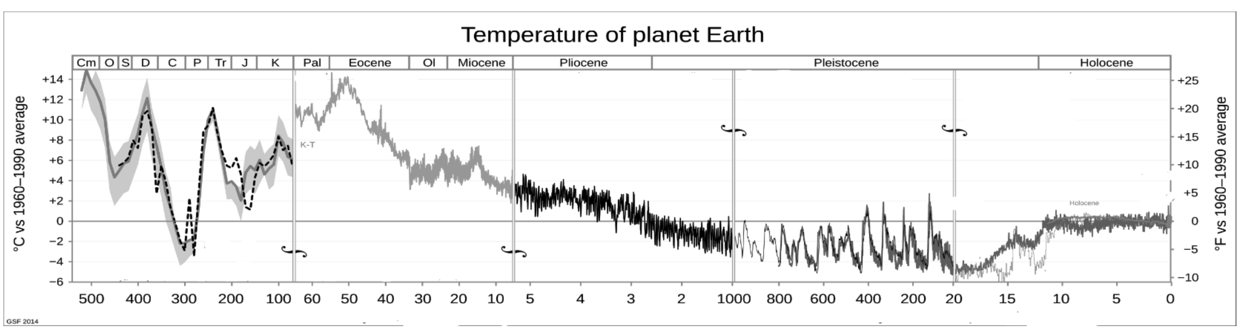
Taking Responsibility in the Anthropocene Epoch

Anthropogenic changes to the Earth's atmosphere have, for the first time, become significant drivers of changes in the planetary climate. This is part of a larger picture: we have entered an era when human beings have become change-drivers comparable in power to the most dramatic natural phenomena. The entire planet's existence is being shaped by human intervention on a scale never seen before. Humanly-generated material now likely outweighs the entire biomass of the Earth,[16] human activity massively impacts virtually every location on the planet,[17] and we may end up responsible for the sixth mass extinction event the Earth has experienced.[18] The Earth could be said to have entered the Anthropocene age, a time when humanity is the dominant influence on ever-more phenomena on a global scale.

The central question of our age may well be: Will humanity take responsibility for the power it increasingly exerts?

Concerningly, despite many efforts to reduce the current production of greenhouse gases, there are strong indications that this will continue to increase. First, ever more people are seeking and attaining the consumption levels of goods and energy typical of the most resource-intensive nations, entailing up to a thousand-fold increase in their energy consumption.[19] Second, new, high-energy-consuming industries, such as cryptocurrencies, data analytics, and generative artificial intelligence, are rapidly accelerating the demand for energy. Neither of these tendencies is likely to slow in the near future.[20]

In light of these challenges, perhaps it is time to recognize that the production of greenhouse gases is a symptom of a deeper problem: the desire to consume ever greater amounts of goods and information, to possess every greater wealth, to enjoy ever more extensive opportunities for travel and entertainment, and to exercise control over ever greater realms of nature. It is hard to imagine how the exponential rise in greenhouse gas production and thus in temperature will ever be brought under control without humanity learning to manage the ultimate driver: our exponentially increasing desires. Can we learn to be satisfied with a sufficiency of goods and capital, with relevant information, with living in and caring for our local environments, with community, and with a cooperative relationship with nature?



Hundreds of millions of years	Tens of millions of years	Millions of years	Hundreds of thousands of years	Thousands of years

Figure 7: Temperature averages at five different time scales

16 Sandra Laville, "Human-Made Materials Now Outweigh Earth's Entire Biomass – Study," *The Guardian*, December 9, 2020, sec. Environment, https://www.theguardian.com/environment/2020/dec/09/human-made-materials-now-outweigh-earths-entire-biomass-study.

17 For example, microplastics permeate the entire ocean, artificial chemicals all the waterways, and pollutants the entire atmosphere.

18 Bob Yirka, "Anthropocene 'Sixth Mass Extinction' Event Predicted to Be Worse than Previously Thought," May 24, 2023, https://phys.org/news/2023-05-anthropocene-sixth-mass-extinction-event.html.

19 Our World in Data, "Primary energy consumption per capita," https://ourworldindata.org/grapher/per-capita-energy-use.

20 On the other hand, the search for new energy sources has shown some promising results; much depends upon success in this area.

Synthesis

When the diverse timescales and timeframes discussed above are placed on a continuous graph, their relationship can be more readily visualized (Figure 7). Here you can see the Earth's temperature varying chaotically on the largest timescale, falling dramatically over 50 million years, cycling rhythmically over the last million years, and staying virtually uniform for the last 10 thousand years. The recent surge in temperature is barely visible at the very end of this graph; it is still quite small in comparison to these other changes.

All of these tendencies are still active today. Volcanic action, the movement of the continental plates, asteroids, and other singular events continue to be potentially significant change agents in unpredictable ways. Any initial change—whether warming, e.g. from anthropogenic greenhouse gas emissions, or cooling, e.g. from the loss of the ocean conveyor—may start a feedback loop that can last 50-million years. The Milanković cycles continue to be driven by the rhythms of Earth's orbital path, axial tilt, and precession. The astronomical factors keeping temperatures level are expected to continue to do so for thousands of years. Anthropogenic warming due to greenhouse gas production is accelerating. Tipping-point events, such as the Atlantic Meridional Ocean Circulation shutting down, are tremendous vulnerabilities.

To imagine these as all simultaneously active is to comprehend both nature's complexity and humanity's rising responsibility. How will we ride the tide, involving as it does so many complex factors? Will we look within as well as outside of ourselves to find both the problems and their solutions?

Harlan Gilbert *has published articles on scientific, pedagogical, and philosophical themes and a book on the role of child development in pedagogy. He lectures in the US and internationally from an anthroposophical perspective, and for 22 years has taught math, science, and philosophy at Green Meadow Waldorf School. His educational journey took him through studies in mathematics, physics, and engineering at Yale, literature and philosophy at Reed, and education at Emerson and Sunbridge Colleges, culminating with a PhD in Transformative Studies from the California Institute of Integral Studies; his dissertation explores the expansion of human identity.*