Lecture 4: Perturbations to the Carbon Cycle

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- The role and response of the ocean in the carbon cycle.
- Future scenarios for Earth.

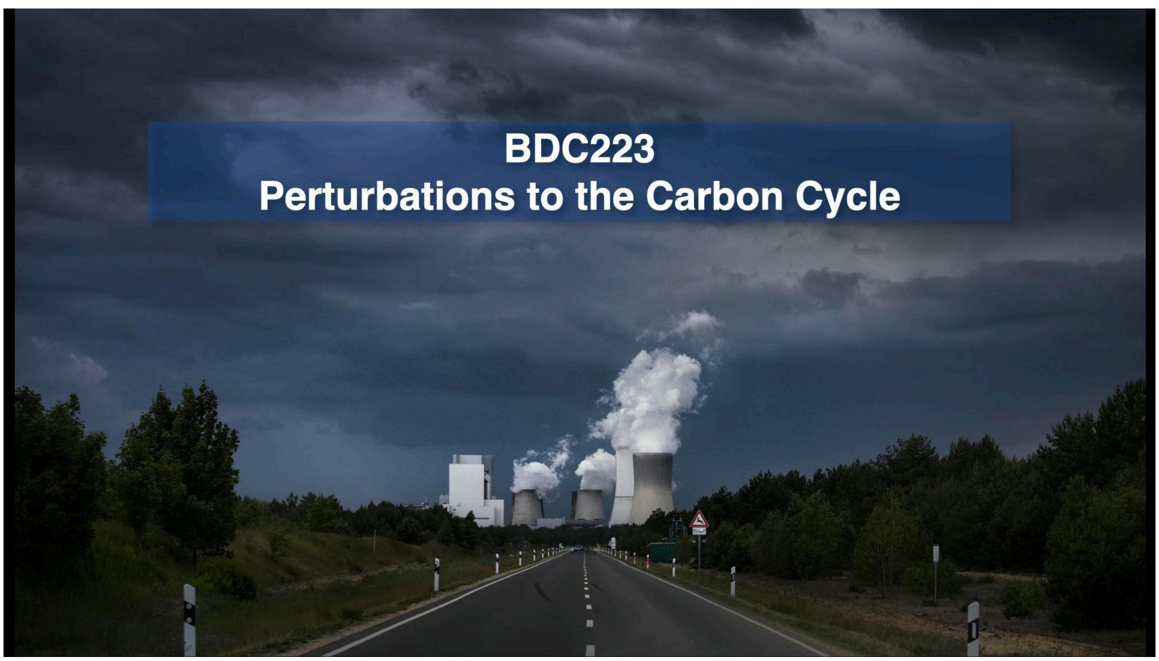
Aims

This lecture aims to provide you with a comprehensive understanding of the carbon cycle and its central role in driving climate change. You will explore the history of climate science, focusing on key figures like Svante Arrhenius, Guy Callendar, and Charles Keeling, whose contributions shaped our current understanding of global warming and atmospheric carbon. In the lecture, we will also cover how the carbon cycle influences the Earth's heat content, the atmospheric and oceanic responses to increased carbon levels, and how these processes contribute to global change. Finally, you will briefly look at some future climate scenarios so as to develop insight into the potential consequences for Earth's ecosystems, with a particular focus on the implications for plant ecophysiology.

Learning Outcomes

After you've mastered this lecture's content, you will be able to:

1. Provide an overview of the carbon cycle and explain its importance in the context of climate change, particularly how carbon moves between the atmosphere, biosphere, oceans, and lithosphere.
2. Recall the contributions of key historical figures—Svante Arrhenius, Guy Callendar, and Charles Keeling—in shaping the science of climate change and the importance of their work in modern climate models.
3. Explain the role of the carbon cycle in driving climate change, including how anthropogenic carbon emissions disrupt natural carbon processes and contribute to global warming.
4. Explain the atmospheric response to increased carbon dioxide, focusing on the increase in heat content and the subsequent changes in global temperature and weather patterns.
5. Describe the role of the ocean in the carbon cycle, including its ability to act as a carbon sink, how it moderates global temperatures and pH, and the long-term consequences of oceanic carbon absorption on marine ecosystems.
6. Evaluate future climate change scenarios, discussing the potential impacts of continued carbon emissions on Earth's climate, ecosystems, and plant ecophysiology, and the importance of mitigation strategies.



1 Introduction: The Carbon Cycle

So, for today's lecture, we are going to talk a bit about the importance of the carbon cycle to plants. Of course, the carbon cycle is extremely important to plants because it unites light, carbon, and water in the process of photosynthesis. But we also know, of course, that the carbon cycle has changed over the last 250 or so years as a result of industrialisation. It is important, then, to understand the physics and the changes to the Earth system that are leading to this changing carbon cycle.

When I speak about the carbon cycle, the main way people are affected is via climate change, which is a small subset of what we call global change. Global change is comprised of all those various things we referenced at the end of Tuesday's lecture, including biodiversity loss, changes to the hydrological cycle, the nitrogen and phosphorus cycles, and all of those aspects discussed in the planetary boundaries set of lectures. So, the carbon cycle and climate change form one of those aspects of global change.

As we have seen, we are already rapidly accelerating towards thresholds—thresholds which, if exceeded, will take us into uncharted and dangerous territory. In fact, we are arguably already there. I'll explain to you shortly that no modern human has ever experienced the kinds of climatic phenomena that we are experiencing today, so it is quite dangerous for people and for much of the rest of life on Earth.

Today I aim to provide you with an overview of climate change: what is known about climate change —not so much its contemporary science, but more the history, seeing when people first started thinking about it. Today's lecture will not be particularly long. I want to talk about the history of climate change, what we know today, and to contextualise our current circumstances within what is known about human development over the last 10,000 or so years.

2 Climate Change: Not a Recent Realisation

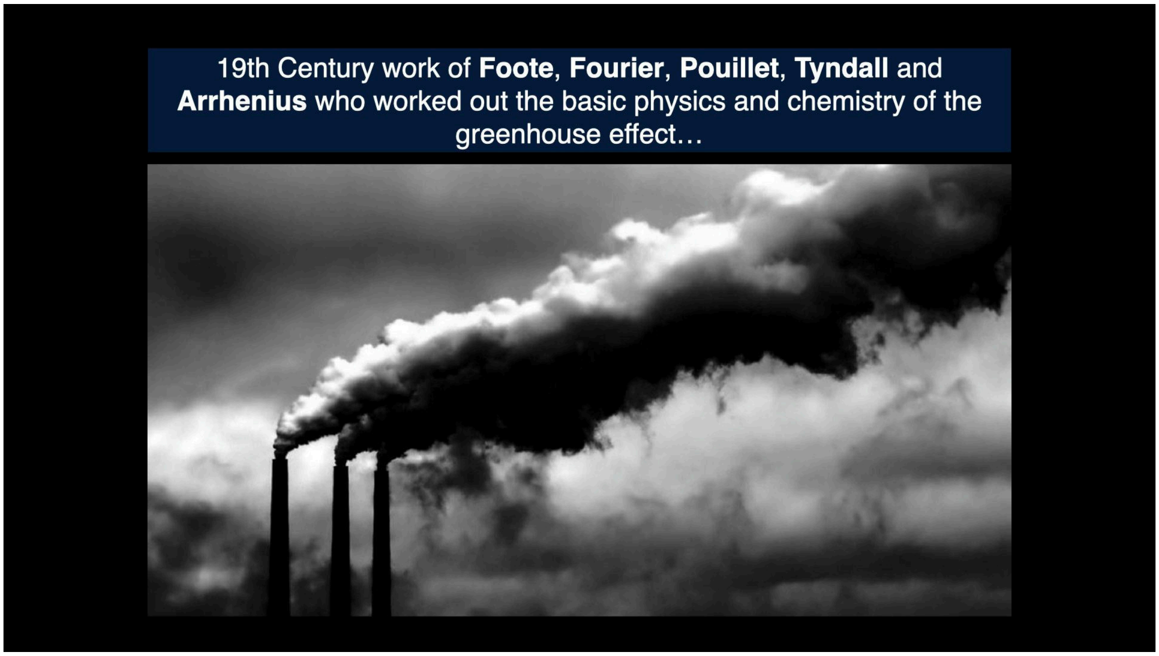
What we know about climate change is not recent, in the sense that the idea of climate possibly changing—or at least the understanding that gases in the atmosphere contribute towards climate change—has been around for a long time. When I refer to climate change, I generally mean that, on average, the world's climate is warming up. The average is an important concept, of course, because there are places on the planet that are actually cooling down slightly.

For instance, around the coastline of South Africa, from De Hoop all along the west coast towards the border with Namibia, the ocean is in fact cooling down in certain places. So, climate change, though global temperatures are on average rising, is experienced differently in different regions—it is heterogeneous, not evenly distributed.

Projections for the future of Africa, for example, show that in the next 50 to 100 years, Africa may be warmer by six to seven °C (°C), which is far more than the average elsewhere on the planet. Thus, Africa is experiencing a larger degree of climate change relative to the rest of the world; but globally, the net warming is positive.

3 Historical Development of Climate Change Science

3.1 The First Experiments and Realisations

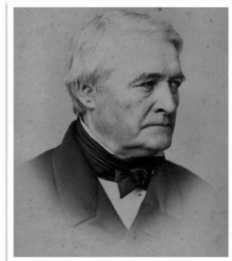


Our understanding of how the world is changing, and how certain gases contribute to that change, started in the late 1800s. There are a few important names to remember: Fourier, Pouillet, Tyndall, and Arrhenius among them.

Joseph Fourier
21 March 1768 to 16 May 1830
French physicyst and mathematician

He considered that Earth's atmosphere might act as an insulator (by trapping 'dark rays' from the ground), and as such is credited with the first arguments for the existance of the greenhouse effect.

1820s

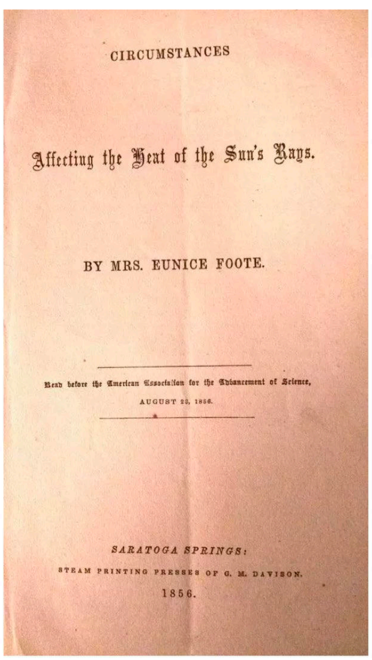


Claude Pouillet
16 Feb 1790 to 14 June 1868
French physicyst

In 1838, he proposed that water vapour and CO_2 light trap infrared radiation and cause a warming of the atmosphere, but he could not provide ecvidence for this claim.

1838

These individuals worked more than 150 years ago on the basic physics and atmospheric chemistry associated with climate change. The scientific foundation explaining our current understanding of climate change thus existed over a century ago.



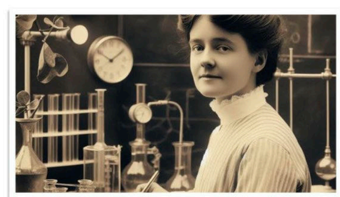
CIRCUMSTANCES

Affecting the Heat of the Sun's Rays.

BY MRS. EUNICE FOOTE.

Read before the American Association for the Advancement of Science,
AUGUST 23, 1856.

SARATOGA SPRINGS:
STEAM PRINTING PRESSES OF G. M. DAVISON.
1856.



Eunice N. Foote
17 July 1819 to 30 September 1888
Scientist, inventor, and women's rights campaigner

Early work on the sun's warming effect on air, specifically, how this was increased by water vapour and carbonic acid gas (carbon dioxide).

Detected the cause of the greenhouse effect.

1856

The first notable experiment was published in 1856 by Eunice Foote, an American scientist who performed a very simple experiment. She placed different kinds of gases in jars, including normal air, water vapour, and what was then called "carbonic acid"—that is, carbon dioxide. She exposed these jars to sunlight and measured, using a thermometer, how quickly each jar warmed up depending on its contents. She observed that the jar containing carbon dioxide became significantly warmer than the others and, when removed from the sun, took much longer to cool down.

> She described filling glass jars with water vapour, carbon dioxide and air, and comparing how much they heated up in the sun. She explained:
>
> "*The highest effect of the sun's rays I have found to be in carbonic acid gas […]. The receiver containing the gas became itself much heated–very sensibly more so than the other–and on being removed, it was many times as long in cooling.*"
>
> "*An atmosphere of that gas would give to our earth a high temperature; and if as some suppose, at one period of its history the air had mixed with it a larger proportion than at present, an increased temperature from its own action as well as from increased weight must have necessarily resulted.*"

Foote concluded that an atmosphere containing higher concentrations of carbon dioxide would give the earth a higher temperature. She speculated that if, at some period in history, the air had a higher proportion of carbon dioxide, increased temperature must necessarily have resulted. She deduced that, in deep history, when there was more carbon dioxide in the atmosphere, the earth would have been warmer. Water vapour, she found, acted in a similar manner. Both gases trap heat and retain it longer, suggesting that early earth, with higher atmospheric concentrations of these gases, would have been warmer as a result.

3.2 John Tyndall's Confirmation

THE
LONDON, EDINBURGH AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.

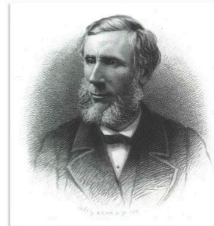
[FOURTH SERIES.]

SEPTEMBER 1861.

XXIII. *On the Absorption and Radiation of Heat by Gases and Vapours, and on the Physical Connexion of Radiation, Absorption, and Conduction.—The Bakerian Lecture. By* JOHN TYNDALL *Esq., F.R.S. &c.**

[With a Plate.]

§ 1. THE researches on glaciers which I have had the honour of submitting from time to time to the notice of the Royal Society, directed my attention in a special manner to the observations and speculations of De Saussure, Fourier, M. Pouillet, and Mr. Hopkins, on the transmission of solar and terrestrial heat through the earth's atmosphere. This gave practical effect to a desire which I had previously entertained to make the mutual action of radiant heat and gases of all kinds the subject of an experimental inquiry.



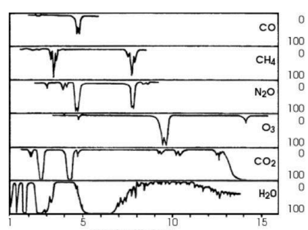
John Tyndall
2 August 1820 to 4 December 1893
Professor of Natural Philosophy (Physics) at the Royal Institution in London

Irish physicist John Tyndall does not appear to have heard of Foote's work when he started on a similar line of inquiry. His publications are more extensive and include accurate quantification of how much different gases absorbed infrared radiation – "radiant heat" – from the sun.

He is commonly credited with proving the greenhouse effect, which underpins the science of climate change.

1861

A few years later, John Tyndall, an Irish physicist known for the Tyndall effect, conducted similar experiments without knowledge of Eunice Foote's prior work. Tyndall expanded on her findings with more detail and precision. He investigated not only carbon dioxide and water vapour, but also how different wavelengths of light, particularly in the infrared spectrum, interact with various gases.



Tyndall's research on the radiative properties of gases. A noted large differences in the efficiency of "perfectly colorless and invisible gases and vapors" to absorb/transmit radiant heat. He saw that oxygen, nitrogen, and hydrogen are almost transparent to radiant heat, while other gases are fairly opaque.

According to his experiments, many greenhouse gases, such as carbon monoxide, methane, nitrous oxide, ozone, carbon dioxide, and water vapour, have different abilities to absorb radiant energy within wavelengths from about one to fifteen micrometres. These gases are present in the atmosphere and are increasing over time due to human activity, such as the burning of fossil fuels.

Tyndall showed, for instance, that carbon monoxide absorbs little infrared radiation until around five micrometres, where its absorbance spikes. Methane traps heat at different points, mostly at around 3.2 and 8.5 micrometres. The absorbance of these gases means that they capture certain wavelengths of infrared energy, which translates into heat trapped within the atmospheric system.

All of these different gases, present in the atmosphere all the time, are able to trap heat from radiation at various characteristic wavelength ranges. Tyndall's work, alongside that of Eunice Foote, provides the foundational experimental evidence for our current understanding of how atmospheric gases contribute to the greenhouse effect.

3.3 Questions on Measurement Techniques

Student Question: How was absorbance measured and how were these gases extracted from the atmosphere?

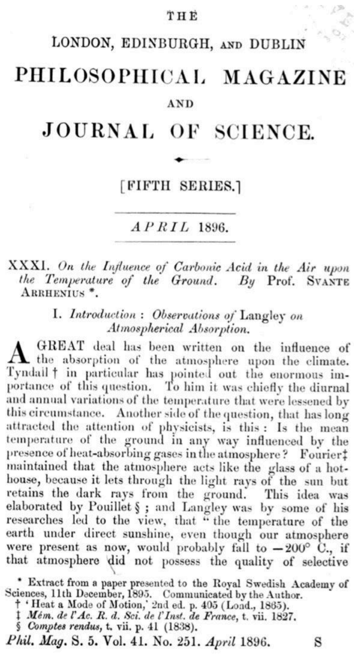
Their measurement techniques relied on instruments that were precursors to today's spectrophotometers—simpler, but based on similar principles. They used prisms to diffract light into a spectrum and would then measure the intensity of light as it emerged, with different components measured by suitable sensors. The nature of the instrument is not completely clear to me at this moment, but it would rely on diffraction to create measurable separations in the light. As we discuss photosynthesis later, we'll encounter analogous experiments, some of which employed phototactic or aerotactic bacteria as biological sensors of oxygen production, indirectly inferring light absorbance at certain wavelengths.

Today, we use instruments such as an IRGA—an infrared gas analyser—for precise measurement of greenhouse gases. This involves shining a beam of infrared light at a known wavelength through a tube filled with atmospheric gas. The decrease in intensity from the source end to the detector is the absorbance, from which one can infer the concentration of greenhouse gases present. Modern detectors, such as those in spectrophotometers, are highly sensitive and can be tuned to specific wavelengths for meticulous measurement.

Student Question: Was the experiment conducted in the dark?

The experiment could be conducted in the dark; however, visible light does not interact with greenhouse gases in the way infrared does. Only infrared radiation is relevant here. Even when it appears dark (at night), there is still plenty of infrared radiation in the environment. The critical factor in the experiment is to ensure that only the intended beam of infrared radiation interacts with the gas in the tube, with other sources of infrared minimised or accounted for, so that only the absorbance by the test gas is measured.

3.4 Svante Arrhenius and The Model of Earth Systems


THE

LONDON, EDINBURGH, AND DUBLIN

PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

[FIFTH SERIES.]

APRIL 1896.

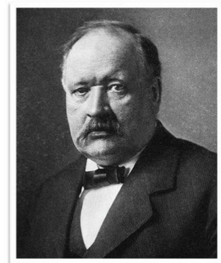
XXXI. *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground. By* Prof. SVANTE ARRHENIUS *.

I. *Introduction : Observations of* Langley *on Atmospherical Absorption.*

A GREAT deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall † in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of the temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this : Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier‡ maintained that the atmosphere acts like the glass of a hothouse, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet § ; and Langley was by some of his researches led to the view, that "the temperature of the earth under direct sunshine, even though our atmosphere were present as now, would probably fall to −200° C., if that atmosphere did not possess the quality of selective

* Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December, 1895. Communicated by the Author.
† 'Heat a Mode of Motion,' 2nd ed. p. 405 (Lond., 1865).
‡ *Mém. de l'Ac. R. d. Sci. de l'Inst. de France*, t. vii. 1827.
§ *Comptes rendus*, t. vii. p. 41 (1838).

Phil. Mag. S. 5. Vol. 41. No. 251. *April* 1896. S



Svante Arrhenius
19 February 1859 to 2 October 1927
Professor of Physics at Stockholm's Högskola (Stockholm University)

The first to use basic principles of physical chemistry to estimate the extent to which increases in atmospheric carbon dioxide are responsible for Earth's increasing surface temperature.

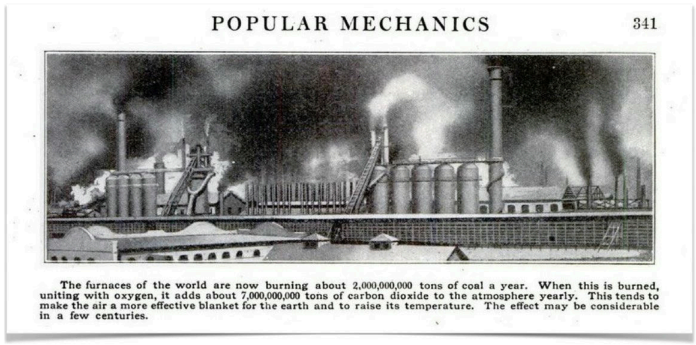
1896

A few years after Tyndall, Svante Arrhenius, a name known also from chemistry for his work on pH and ionic dissociation, extended previous findings. Instead of confining his interpretation to the laboratory, Arrhenius realised that by understanding how gases absorb infrared radiation, he could extrapolate an estimate of how carbon dioxide concentrations affect temperatures at the earth's surface itself—not just in a jar.

His approach was still crude but remains the foundation of climate change science: the idea that by measuring carbon dioxide concentrations, one could estimate corresponding changes in earth's surface temperature. Arrhenius thus moved climate change science from the realm of curiosity towards large-scale understanding, showing its importance for the environment experienced by both humans and plants.

3.5 Early Recognition of Human Influence on Climate

Aug. 14, 1912, in a couple of New Zealand newspapers, the Rodney and Otamatea Times and Waitemata and Kaipara Gazette. Also in Popular Mechanics…



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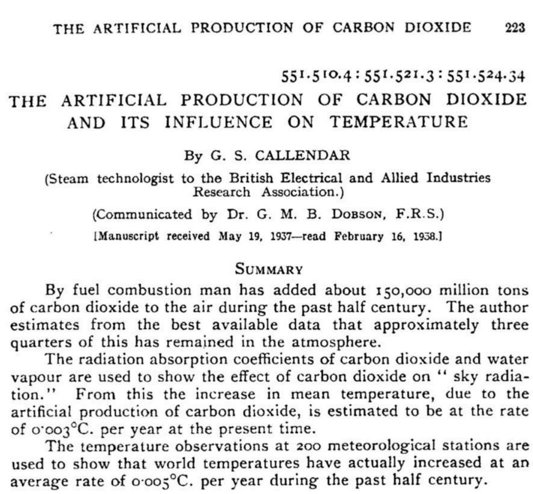
The furnaces of the world are now burning about 2,000,000,000 tons of coal a year. When this is burned, uniting with oxygen, it adds about 7,000,000,000 tons of carbon dioxide to the atmosphere yearly. This tends to make the air a more effective blanket for the earth and to raise its temperature. The effect may be considerable in a few centuries.

1912

At the beginning of the twentieth century, this knowledge began to enter public discourse. In 1912, a newspaper article in New Zealand speculated for the first time that the burning of coal—combining carbon with atmospheric oxygen to produce CO_2—would eventually lead to planetary warming, based on Arrhenius's work. This early speculation tied industrial emissions to potential climate consequences.



THE ARTIFICIAL PRODUCTION OF CARBON DIOXIDE 223

551.510.4 : 551.521.3 : 551.524.34

THE ARTIFICIAL PRODUCTION OF CARBON DIOXIDE AND ITS INFLUENCE ON TEMPERATURE

By G. S. CALLENDAR

(Steam technologist to the British Electrical and Allied Industries Research Association.)

(Communicated by Dr. G. M. B. DOBSON, F.R.S.)

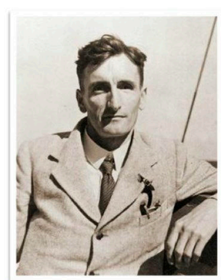
[Manuscript received May 19, 1937—read February 16, 1938.]

SUMMARY

By fuel combustion man has added about 150,000 million tons of carbon dioxide to the air during the past half century. The author estimates from the best available data that approximately three quarters of this has remained in the atmosphere.

The radiation absorption coefficients of carbon dioxide and water vapour are used to show the effect of carbon dioxide on "sky radiation." From this the increase in mean temperature, due to the artificial production of carbon dioxide, is estimated to be at the rate of 0·003°C. per year at the present time.

The temperature observations at 200 meteorological stations are used to show that world temperatures have actually increased at an average rate of 0·005°C. per year during the past half century.



Guy S. Callendar
9 Feb 1898 to 3 Oct 1964
Steam engineer and inventor

He was the first person to show that Earth's temperature had risen during the previous 50 years, and hypothesised that this might be explained by the increase in CO_2 in the atmosphere.

1938

Guy Callendar, a British engineer and amateur meteorologist in the 1930s. In 1938 he published, “The Artificial Production of Carbon Dioxide and Its Influence on Temperature.”

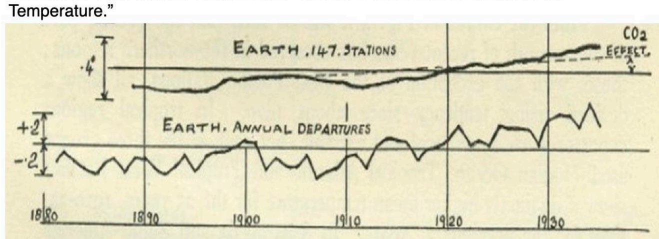
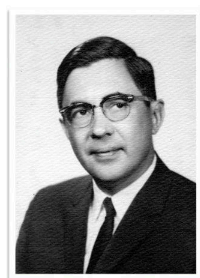


FIG. 4.—Temperature variations of the zones and of the earth. Ten-year moving departures from the mean, 1901-1930, °C.

Proving more concrete was the work of Guy Callendar, an engineer, who in the early twentieth century estimated the increase in mean global temperature due to artificial addition of CO_2 from burning coal. His calculations put the warming effect at just 0.003°C per year [attention: this value is lower than modern-day estimates based on recent emissions], a figure so small it was easily overlooked at the time and treated as a curiosity rather than a pressing concern.

He proved that CO_2 was a key driver of the greenhouse effect:

- Plass, G.N., 1953. Science: Invisible Blanket. Time. May 25, 1953
- Plass, G.N., 1956. Infrared Radiation in the Atmosphere, American J. Physics 24, p. 303-21.
- Plass, G.N., 1956. Carbon Dioxide and the Climate, American Scientist 44, p. 302-16.
- Plass, G.N., 1956. Effect of Carbon Dioxide Variations on Climate, American J. Physics 24, p. 376-87.
- Plass, G.N., 1956. The Carbon Dioxide Theory of Climatic Change, Tellus VIII, 2. (1956), p. 140-154.
- Plass, G.N., 1959. Carbon Dioxide and Climate, Scientific American, July, p. 41-47.



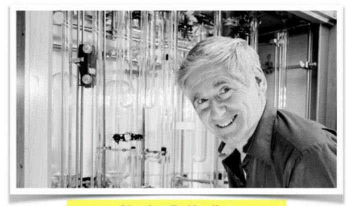
Gilbert Plass
22 March 1920 to 1 March 2004
First professor of Atmospheric and Space Science at the Southwest Center for Advanced Studies (now the University of Texas at Arlington)

“At its present rate of increase, the CO2 in the atmosphere will raise the earth's average temperature 1.5° Fahrenheit every 100 years. ... for centuries to come, if man's industrial growth continues, the earth's climate will continue to grow warmer.” Plass (1953).

1956

Following Callendar, Gilbert Plass added more rigour to Arrhenius and Tyndall’s work, analysing the specific heat-trapping contributions of various greenhouse gases to the atmosphere, though there was still little hard evidence connecting atmospheric CO_2 to observed temperature increases, due to the absence of accurate measurements of global CO_2 concentrations.

3.6 Direct Measurement: Charles Keeling and the Keeling Curve



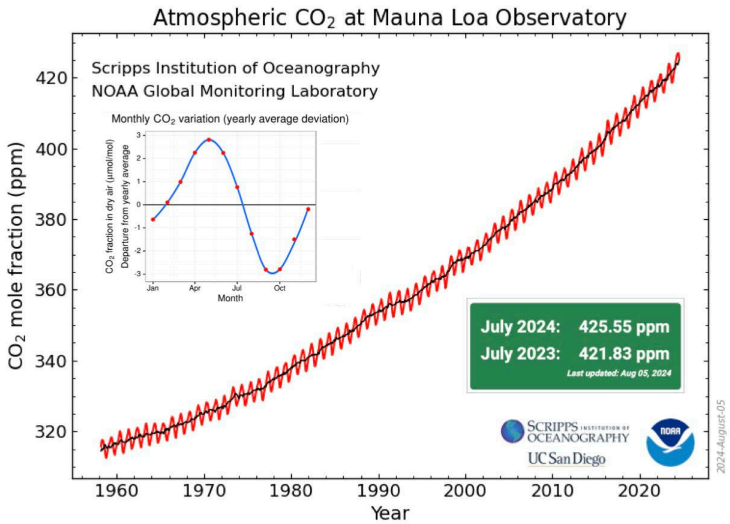
Charles D. Keeling
20 April 1928 to 20 June 2005
Professor of Oceanography, Scripps Institution of Oceanography

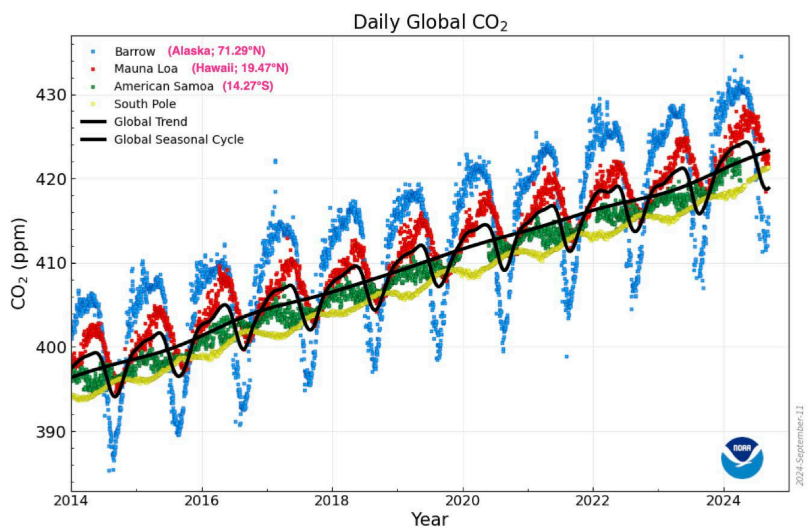
- first alerted the world to the possibility of anthropogenic contribution to the “greenhouse effect” and global warming
- the Keeling Curve measures the progressive buildup of carbon dioxide, a greenhouse gas, in the atmosphere

Known for what is now called the ‘Keeling curve’, a continuous record of data that documents, to this day, the rising concentration of CO_2 in Earth’s atmosphere.

1961

It was not until Charles Keeling, an oceanographer, began careful direct measurements of atmospheric CO_2 in Hawaii, that the relationship between emissions and atmospheric composition became irrefutable. On the summit of Mauna Loa, he established an observatory and, year after year, measured CO_2 concentrations.





"The figure shows daily averaged CO_2 from four GML Atmospheric Baseline observatories; Barrow, Alaska (in blue), Mauna Loa, Hawaii (in red), American Samoa (in green), and South Pole, Antarctica (in yellow). The thick black lines re smoothed seasonal curves and the smoothed, de-seasonalized curves for each of the records. These lines are a very good estimate of the global average levels of CO_2" (Credit: NOAA Global Montoring Laboratory).

The resulting data showed not only an annual zigzag pattern (seasonal variation in CO_2), but a clear, uninterrupted upward trend. In 1958, CO_2 was measured around 315–318 ppm; today it is at about 420 ppm, and climbing.

Keeling's measurements revealed that CO_2 is continually increasing due to ongoing fossil fuel combustion, deforestation, and industrial activity. This increase is observed even four kilometres deep in the ocean, showing that every part of the planet is being affected—there is nowhere immune to the effects of this rising CO_2 concentration.

If humanity suddenly switched to 100% renewable energy, the rate of increase in CO_2 would slow but not stop; some further increase is effectively locked in, leaving the question merely about how quickly or slowly things worsen. The reality is that such an overnight global switch is currently politically and practically impossible, so the future likely lies somewhere between worst-case and best-case scenarios.

3.7 The Effect of COVID-19 Lockdowns

Student Question: Did the COVID-19 lockdowns have a measurable effect on the CO_2 trend?

During lockdown, pollution and emissions did decrease temporarily, with satellite data showing a significant blip in atmospheric pollutants over South Africa, for instance. However, as restrictions eased, industries sought to compensate for lost time, causing emissions to rebound quickly. Thus, any effect on the overall CO_2 curve is likely to be negligible; the long-term trend remains upward. Future data will clarify whether there is any observable dip due to lockdown, but I do not expect a significant long-lasting deviation.

4 The Global Nature of the Carbon Cycle

It is worth remembering that the atmosphere is a globally coupled system. While Keeling's observatory in Hawaii provides the longest-running data set, simultaneous measurements in Antarctica, South Africa, and elsewhere show parallel increases. CO_2 added to the atmosphere anywhere will be detected everywhere after only a short delay, as air mixes globally.

Government policies and decisions at all levels—including in South Africa—thus affect the planet as a whole. Local restrictions on distributed solar energy, for example, have global ramifications, demonstrating the interconnectedness of carbon emissions.

5 Assignment: The Seasonal Fluctuation of CO_2

To end today's lecture, I have a small assignment for you, which will count towards your continuous assessment mark. I want you to consider the 'zigzag-like' pattern on the Keeling Curve, where every year CO_2 rises and falls in a regular cycle, yet year after year the whole curve trends upward.

Please write a brief explanation—perhaps a paragraph, half a page—describing why CO_2 is low in January, peaks around April or May, and drops again toward September. What accounts for this seasonal pattern? Your answers are due by Friday at 11:55 pm, to be submitted via IKAMVA. I'll send details of the formatting requirements. This ties directly to the topic of this module and is a question that integrates several core ideas we have discussed.

If you have any questions, please let me know. We will pick up on the theme of climate change in Monday's lecture, delving further into its scientific, ecological, and societal impacts.

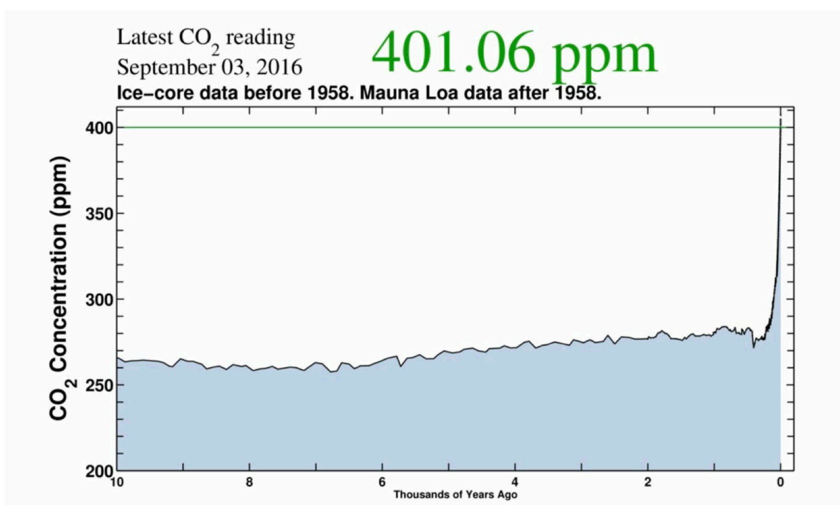
6 The Keeling Curve and the Historical Context of CO_2

Let me continue from where I left off last time. I ended with a discussion on the graph displaying the increase in carbon dioxide in the atmosphere over the last sixty or so years. This graph, as you see it there, shows a wiggly line rising steadily from 1958 to the present day. Eventually, this plot became known as the Keeling Curve, named after the scientist who originally began collecting the data behind it—Charles Keeling. Today, the Keeling Curve stands as the basis of our modern understanding of climate change, backed by this and similar sets of observations.

What's happened in the intervening sixty years is that people have managed to extend this graph further to the left, using various scientific methods that allow us to peer deeper into our planet's history. We can now look further back in time and, similarly, using global climate models, we are even able to project forward, about a hundred or a hundred and fifty years into the future. After we are all gone, we do have a reasonable degree of certainty about what the future world will be like, at least with regard to the climate, as the mathematics and science align quite reliably. We'll delve into the predictive capacity of these models later.

The important point to note now is that in the Keeling Curve, the small section we previously focused on is just the recent part, essentially the right-hand section of this extended timeline, whereas the area labelled "10 to 0" corresponds to the last ten thousand years—the era of recorded human civilisation. I'll display another graph shortly that extends even further back, but the take-home message is that the vast majority of what we know as human history and civilisation falls within these last ten thousand years.

7 Human Development and Climate Stability



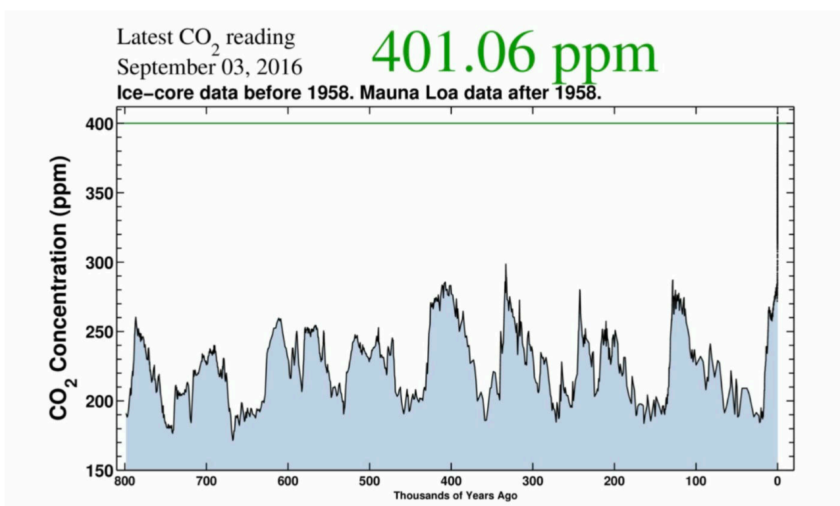
It was during this period—about ten thousand years ago—that all the hallmarks of modern humanity started to emerge. Towns and cities arose, agriculture began, and the domestication of animals took place. This was also when the famous cave paintings were made in places like France and northern Europe, with a few even older examples elsewhere.

Most fundamentally, everything we recognise as human development has occurred within the last ten thousand years. Around six to five and a half thousand years ago, we start seeing the first written records, preserved on early scripts and papyrus scrolls. This is also the period when the Egyptian pyramids were constructed. About two thousand years ago, some dude called Jesus Christ was also born, or at least the idea of him as some important figure was recorded, during this timeline. In the two millennia since, he has developed for himself quite a following of sheep.

My point is that all recorded human history has developed while atmospheric CO_2 levels remained below around 250 to 260 parts per million. Nothing in the archaeological or historical record suggests modern humanity has ever experienced—and certainly never thrived in—CO_2 conditions higher than that. This is the point of reference.

Today, however, we're above 400 parts per million—currently about 420. No modern human has ever lived in such a high-CO_2 world. Humanity developed in a period of low, stable CO_2, but now CO_2 concentrations are soaring, and people find themselves in truly unprecedented conditions. While our models give a solid sense of how Earth's systems—like temperature, precipitation, sea levels, and winds—will behave, we cannot say with confidence how humans will cope socially, physiologically, or culturally with this "uncharted territory". I'll show you yet another graph on this shortly.

8 Climate Change in Deep Time

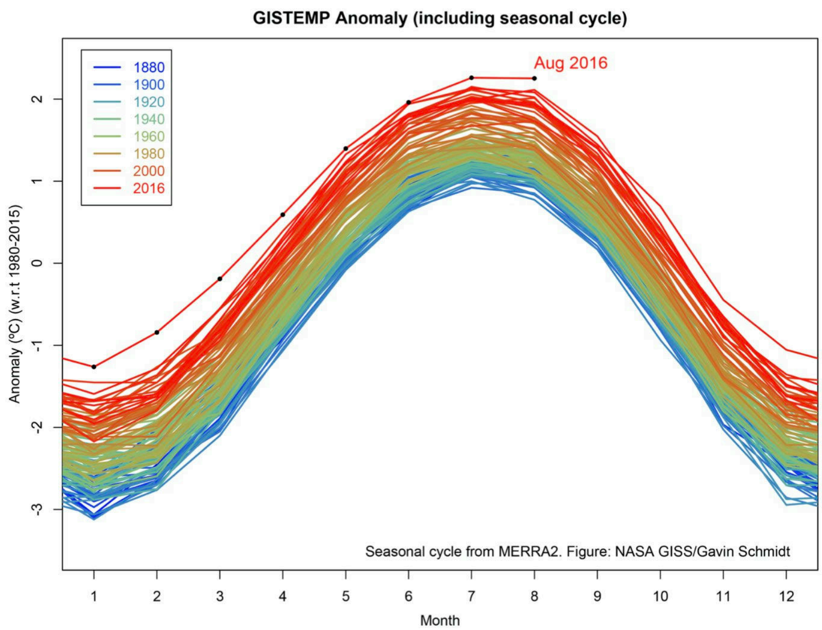


If we push our perspective further back—ten thousand years ago to 800,000 years ago—the data show a recurring pattern of rises and falls in CO_2 and global temperatures. These are the glacial and interglacial periods, tied to natural climate cycles. You can see it on the graphs—ups and downs corresponding to ice ages and warmer interglacial phases. When CO_2 levels are high, we see polar ice caps melting and the world resembling its form from about two centuries ago, before recent melting recommenced. When CO_2 drops, temperatures plummet and ice ages resume.

Climate change sceptics or deniers often point out, "the climate has always changed!", and they're not incorrect in the basic sense—this graph illustrates that. However, at no point in the last 800,000 years did CO_2 ever reach today's levels. It fluctuated between about 180 and 260 parts per million, never once exceeding 300, and certainly never surpassing 400. We are, in measurable terms, in entirely novel territory.

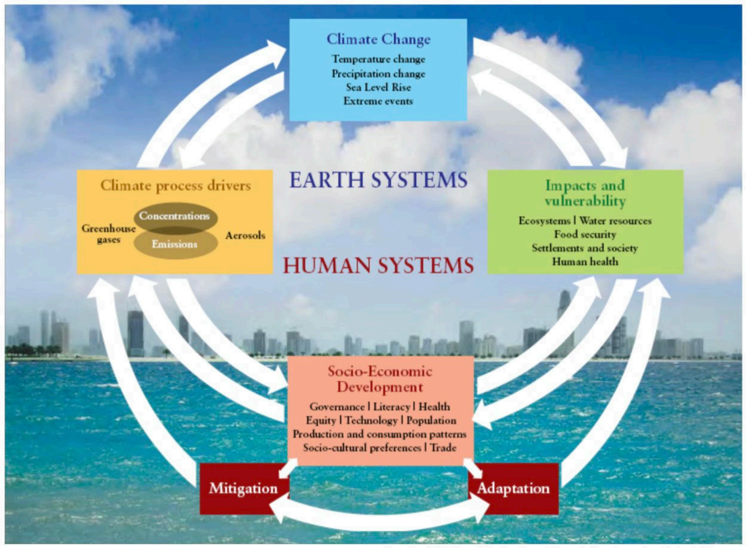
Hominids—our human-like ancestors—appeared around 160,000 to 170,000 years ago; modern humans some 70,000 years back; human societies about ten thousand years ago. Societal development correlated closely with periods of climate stability, which in turn relied on relatively constant atmospheric CO_2. Now, that stability has ended.

9 Observed Temperature Rises



Let's look at a visual representation of temperatures recorded over the last 100 to 120 years. If you animate these records, you see the starting point near 1850; as you progress towards the present, temperatures climb. The warming trend has clearly accelerated over just the last three decades. At first, annual increases were minor, but from the 1970s onwards, the rate of temperature rise steepens dramatically. At present, we're even further down this trajectory—you can easily project future trends from the graph.

10 Why Climate Change Matters: Beyond Just Temperature



From the IPCC Expert Meeting Report: Towards New Scenarios - Technical Summary

Why do I discuss climate change so persistently? Its impact is not merely a matter of rising average temperatures. As I explained previously, warming is not uniform— some regions experience much greater change than others. Globally, however, the average is up. The knock-on effects are far-reaching.

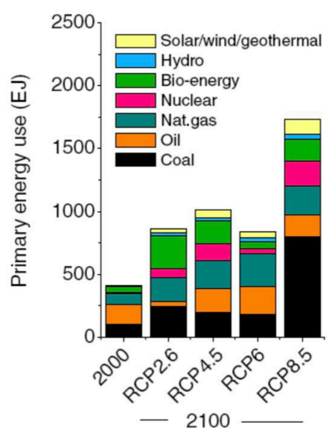
- **Precipitation Patterns:** Rainfall will increase in some areas, but countries like South Africa will see declines. Cape Town, for example, faces a future where the severe drought faced two years ago becomes typical, not exceptional.
- **Sea Level Rise:** Coastal communities—like those living in Sea Point, Cape Town—are under threat as sea levels climb. Notably, around 80% of the human population lives close to coastlines, so massive populations face displacement.
- **Extreme Events:** Extreme heat, strong winds, severe waves, droughts, and heavy rainfall will all become more frequent, more intense, and last longer. This is the very unpredictability now exceeding anything in the modern historical record.

Climate change is thus significant not only in isolation, but because it affects all ecosystems, resources, and social systems, from food security and settlements to health.

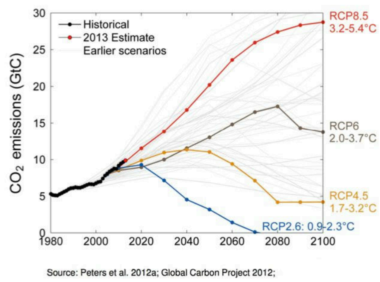
10.1 Climate Change Scenarios

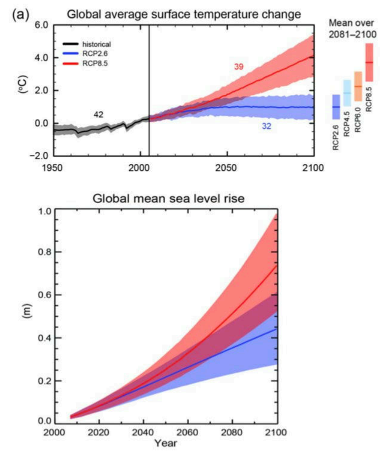
> *"In climate change research, scenarios describe* ***plausible trajectories of different aspects of the future that are constructed to investigate the potential consequences of anthropogenic climate change****. Scenarios represent many of the major driving forces -* ***including processes****, impacts (physical, ecological, and socioeconomic), and* ***potential responses*** *that are important for informing climate change policy. They are used to hand off information from one area of research to another (e.g., from research on energy systems and greenhouse gas emissions to climate modeling). They are also used to explore the implications of climate change for decision making (e.g., exploring whether plans to develop water management infrastructure are robust to a range of uncertain future climate conditions). The* ***goal of working with scenarios is not to predict the future but to better understand uncertainties and alternative futures****, in order to consider how robust different decisions or options may be under a wide range of possible futures".*
>
> **— IPCC AR5**

RCP2.6
RCP4.5
RCP6
RCP8.5



▲ Energy sources by sector (van Vuuren et.al. 2011)





10.2 Impacts on Human Health and Societies

For example, altered rainfall means more standing water in already-wet areas, facilitating waterborne diseases such as diarrhoea, trypanosomiasis, and increased malaria transmission. Already, malaria is reaching areas in South Africa where it was previously unknown, as climate zones shift and mosquitoes migrate southward from Zimbabwe and Mozambique.

Socioeconomic effects are just as pressing. Much unrest in North Africa and in the Arab world now occurs in part because regions are becoming drier and less hospitable, driving displacement and accelerating conflict [attention: while environmental stress is a factor, many conflicts arise from a complex mixture of political, social, and historical causes]. As climate change intensifies, so do its consequences for all interactions between people and the planet.

11 Feedbacks and the Role of Ecosystems

Of particular interest to us in this course are the feedback loops between climate and ecosystems—especially those involving plants, the primary producers. For instance, the reason the Keeling Curve shows a sawtooth pattern—those seasonal wiggles—is because trees and other vegetation take up CO_2 in the growing season, thus reducing atmospheric concentrations, and then release it again in autumn and winter as leaves fall and decay. Fewer trees means less CO_2 is drawn down, and more remains in the atmosphere, exacerbating warming.

Thus, the maintenance and protection of ecosystems, particularly of forests, is vital in addressing climate change. The more primary production—photosynthesis—we have, the more atmospheric CO_2 is converted into biomass and safely stored. Reducing the destruction of forests is therefore absolutely crucial, not only for the environment, but for everyone globally.

12 Mitigation and Adaptation Strategies

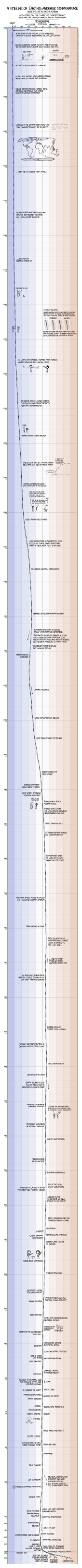
Ten years ago, most climate scientists spoke mainly of mitigation—strategies to reduce greenhouse gas emissions and increase carbon capture. The focus was on what could be done to trap CO_2, limit emissions, and minimise further impact. That was mitigation: offsetting atmospheric loading with active intervention.

Increasingly, the emphasis has shifted to "adaptation". There is now recognition that, regardless of efforts, some degree of change is inevitable, as we are already living with the consequences. Adaptation is about adjusting to the new conditions—learning how humanity and natural systems can best manage and survive in a world transformed by climate change.

Adaptation strategies differ greatly between human systems and biological ones. For this module, our focus will be on the adaptation strategies of plants—understanding what physiological mechanisms they possess to cope with changing environments and, crucially, how plant stresses are managed. Whenever relevant, I'll relate these back to broader global issues, but the primary focus is on ecosystems, and specifically how plants, as primary producers, can and do respond to the changes we are witnessing.

13 A Brief History of Earth's Climate and Human Civilisation

I explain the content of the scrolling figure below the image.


A TIMELINE OF EARTH'S AVERAGE TEMPERATURE
SINCE THE LAST ICE AGE GLACIATION

14 Overview of the Temperature Graph

On the left axis of this particular graph—although it's actually the x-axis due to the orientation we've got here—we have the independent variable, and on the vertical axis, that's the dependent variable. Here, temperature is the aspect that depends on which point in history we're examining. The graph spans from plus four °C to minus four °C, relative to the average temperature over the entire depicted period. Now, the main focus is on this central white band, which is key for our discussion.

The timeline starts at around 20,000 years ago, and as I scroll down, we move steadily towards the present day. So, about 20,000 years ago, the Earth was roughly four °C colder than it is today. I must point out that this is quite a Northern Hemisphere-centric perspective. At some point, I should really produce a similar graphic focusing on South Africa or the African continent, so we can localise our interpretations. For the moment, however, do keep in mind that this particular presentation is fundamentally rooted in North American context.

At that time, Boston—now a relatively verdant city—was actually buried under about a mile of ice. So, back then, the temperature was still about four °C colder than present, and that's reflected by the dotted line tracing temperature changes. From here on, the graph outlines a chronological procession of climate events and human developments.

15 Early Human Migrations and Extinctions

Between 19,000 and 19,500 years ago, humans had already dispersed from Africa and were found throughout Eurasia and even in Australia. Notably, when humans arrived in Australia, their sudden presence led, within around a thousand years, to the extinction of all the large mammals—megafauna—in that region. Today, the largest animals in Australia are kangaroos, but prior to human arrival, truly massive creatures inhabited the continent. The arrival of humans is strongly linked to the rapid die-off of these species. This phenomenon is not unique to Australia; similar patterns were happening elsewhere, including South Africa.

Around 19,000 years ago, evidence shows that people began to create paintings, pottery, rope, and other artefacts of material culture.

16 Climatic Shifts and the Milankovitch Cycle

At approximately 18,500 years ago, there was a slight change in the Earth's orbit—a phenomenon known as the Milankovitch cycle. This event caused Earth to absorb a little more heat in its polar regions, which in turn allowed the great ice sheets to begin melting. The process was gradual at first: as the ice sheets retreated, sea levels rose, but temperature increases remained relatively modest. However, atmospheric CO_2 concentrations began to creep upwards. This was due to various processes, including the re-mineralisation of materials previously trapped beneath the ice.

As more naturally trapped CO_2 entered the atmosphere, warming began to accelerate, though it remained cold by modern standards—still about three °C colder than today.

17 Human Culture and Dispersal

By 15,000 years ago, we see the emergence of cave art—the kind that we now admire as cave paintings, though at the time, people might simply have seen it as graffiti. Some of the oldest examples have been found in France.

At around 14,500 years ago, the ice sheets in Alaska shrank to the extent that the land bridge between Asia and North America, the well-known Bering Land Bridge, disappeared. This development made it possible for humans to enter and populate North America for the first time, giving rise to the ancestors of Native Americans. This migration predates the arrival of Europeans on the continent by many thousands of years.

By 13,500 years ago, New York was no longer under ice, and by 13,000 years ago, species such as the woolly rhinoceros became extinct. At 12,500 years ago, significant flooding occurred in what is now Washington state, due primarily to the rapid melting of glaciers.

18 Rise in CO_2 and Continuing Warming

All the while, CO_2 levels continued to rise, driving further increases in temperature. The ice sheets eventually disappeared even from areas such as Chicago.

By 11,500 years ago, people began to settle in the area now called Syria—formerly known as Mesopotamia—within the region known as the Fertile Crescent. This marks a pivotal point, as humans began to establish small communities and, ultimately, towns and cities. The city of Jericho, one of the earliest known urban settlements, arose during this era, when the Earth's temperature was still about one and a half °C colder than present.

19 Agricultural Revolution and the Holocene

Moving to 10,000 years ago, as temperatures reached a level still somewhat cooler than modern conditions, the first evidence of farming emerges. People first settled in cities and only then does agriculture appear, in response to the demands of a growing, settled population.

About 9,500 years ago, or more specifically around 9,200 years ago, we see the extinction of the sabre-toothed cat. Horses also disappeared from North America, likely due to human impacts. (A quick aside: there's a facetious reference in the source text to Pokémon going extinct at this time, which is, of course, entirely fictional [attention].) As temperatures reached levels comparable to those of the 20th century, cattle were domesticated—around 8,500 years ago. By this point, the ice sheet over Canada had entirely vanished.

From roughly 10,000 years ago to the present, Earth's temperature remained, for the most part, within a relatively narrow band—about one degree Celsius higher or lower than today. This stable period is known as the Holocene. It encompasses the entire span during which humans have been able to build cities, develop stable agriculture, and domesticate animals.

20 Early Civilisations and Technological Developments

By about 7,000 years ago, human settlement is documented in China, which stands as the oldest continuous civilisation in the world. Around 7,500 years ago (5,500 BCE plus the succeeding two thousand years), metalworking begins, along with the invention of the wheel, which, surprisingly, dates to only about 6,000 years ago.

The timeline features several key developments in civilisation—urban life in the Fertile Crescent; Egyptian mummification; the rise of the Indus Valley civilisation; and later, Stonehenge in the UK at about 4,000 years ago. Alphabetic writing appears in Egypt after the development of chariots and further urban expansion.

Written history, iron smelting, and early Greek civilisations also belong to this relatively recent part of our timeline. The peopling of the Pacific and Solomon Islands follows, and then another sequence of events from classical Greece to around 500 BCE, when both Greek and Buddhist traditions were crystallising.

21 Recent History, the Industrial Revolution, and Climate Change

All of the above—essentially everything we know as "civilisation" and "recorded history"—has taken place within this narrow "white band" on the graph, where global temperatures have not deviated by more than about one degree Celsius from present values.

Fast-forwarding to the last few centuries, we reach the invention of the steam engine, which allowed humanity, for the first time, to convert heat energy into mechanical work efficiently—driving the Industrial Revolution. Before this, societies had depended primarily on human and animal labour. Subsequently, developments such as the telegraph and aeroplane emerged, propelling us into the modern era.

Now, as of 2016, we find ourselves not only at the edge of this narrow band but potentially at the threshold of something new. Should we persist with current patterns of fossil fuel combustion—coal, oil, and gas—we are on a trajectory that leads to much warmer global temperatures, with increases possibly in the range of two, three, four, or even five °C above current levels. If, on the other hand, we made a radical change—literally switching off all fossil fuel emissions overnight—we might have a chance to slow the warming, but even then we are now in a climatic regime where no human civilisation has ever previously existed.

This is why climate change is such a critical and urgent topic for us to understand.

Bibliography